CHALMERS

Unfolding the formative phase of gasified biomass in the European Union

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HANS ROBERT A. HELLSMARK

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Göteborg, Sweden 2011

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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Environmental System Analysis
Department of Energy and Environment
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone + 46 (0)31-772 1000
URL: http://www.chalmers.se/ee

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ABSTRACT

In an era of climate change, the process of and time frame for fostering new industries with the capacity of being innovative and able to diffuse a wide range of renewable energy technologies on a large scale has become a pressing issue. In the midst of the creation of such industries are the system builders—without such actors, new technologies and industries would not emerge. In this thesis, a novel conceptualisation of system builders is presented from a technological innovation system (TIS) perspective. The focus is on system builders with the intention of realising the potential of biomass gasification for the production of second-generation transportation fuels and other chemicals. The empirical work covers the historical development of biomass gasification in four countries—Austria, Germany, Sweden, and Finland—leading up to the nine most prominent technology development projects currently in Europe. This thesis analyses: a) who act as system builders in the different national contexts; b) how they learn and enable the emergence of the new system; and c) the limits to their capacity in creating the new and embryonic industry structures. With these insights, policymakers may d) set more realistic goals with respect to future targets and design policy interventions that address the actual system weaknesses of the emerging TIS. It is suggested that second-generation fuels from biomass can only play a very limited role in the fuel market until 2020 at the earliest. For realising the large but long-term potential of the technology, actions must now be taken to shift some of the risks for investors to society at large by funding demonstrations and forming initial markets for fuels that are significantly more expensive than conventional alternatives. Without such markets, the system builders will have great difficulties attracting further actors with complementary competencies, as well as the additional resources necessary to resolve the remaining technical uncertainties and take the required steps towards commercial-scale plants.

Keywords: biomass gasification, second-generation transportation fuels, technical change, system builders, technological innovation systems, technology policy.

OTHER PUBLICATIONS

This thesis consists of the book presented here. However, without the insights made when writing other publications, it would not have been possible to write this in the first place. I would therefore like to highlight these previous publications:

- Hellsmark, H., Jacobsson, S., 2010. Realising the potential of gasified biomass in the European Union — Policy challenges in moving from demonstration plants to large-scale diffusion. Submitted to Energy Policy.

- Hellsmark, H., Jacobsson, S., 2009. Opportunities for and limits to Academics as System builders — The case of realizing the potential of gasified biomass in Austria. Energy Policy 37, 5597-5611.

- Hellsmark, H., 2005. The Co-Evolution of Institutions, Organisations and Renewable Energy Technologies. Licentiate thesis, Department of Technology Management and Economics, Chalmers University of Technology, Gothenburg.

- Jacob, M., Lundqvist, M., Hellsmark, H., 2003. Entrepreneurial transformations in the Swedish University system: the case of Chalmers University of Technology. Research Policy 32, 1555-1568.

Evelien
Eden & Selma

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This thesis is about the role of system builders in the emergence of an industry with the capacity to realise the potential of second-generation fuels. It has been demonstrated how these system builders are dependent on being embedded in a rich, heterogeneous and supportive structure. Their pure survival has, at times, been dependent on the existence of other actors who are ready to save them from ruin. Over the past four decades, these system builders have been able learn, grow stronger and create an embryonic industry structure. If appropriate policymeasures are taken, some of them may even be able to realise their intentions and the large-scale diffusion of second-generation fuels may begin by 2020.

Although not a system builder, I can strongly identify and relate based on my personal experience from writing this thesis. For completing this thesis, I have also been dependent on being embedded in a rich and heterogeneous structure. Without the encompassing support from my supervisor, colleagues, financiers, respondents, friends, and family, this thesis would never have been possible to write. When some days were grey and the road ahead seemed endless, you have inspired me and provided the right reasons to stay focused. For that I am deeply grateful!

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This thesis would not have been possible to write without everyone that has, most generously, taken their time to explain all aspects of gasification and their efforts in realising the knowledge field. Many of you also took the time to comment on earlier drafts of this thesis for which I am deeply grateful. I would like to direct a special thanks to Christopher Higman who provided detailed comments on Chapter III. Useful comments were also received from Magnus Holmén, two anonymous reviewers and participants at the DIME International Conference on "Innovation, sustainability and policy'" 11–13 September 2008, GREThA, University Montesquieu Bordeaux IV, France. Of course, the interpretations of the events in this thesis are mine, as well as the responsibility for potential errors.

Not the least, I would like to thank my family. Without the love and support from my wife, Evelien, this thesis could not have been written. I would also direct thanks to my mother for always reaching out a helping hand. Eden and Selma, you are the most wonderful children a father could hope for.

Bagaregården,
2010-11-28

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Setting the scene

Chapter I
Introduction

Innovations, in terms of new products and services, have been identified as a key factor in the creation of new firms and industries, the re-vitalisation of existing industry structures, and as the main driver behind economic growth, at least since the time of Smith (1776), Marx (1887) and Schumpeter (1934; 1942). Entrepreneur(s), acting as system builder(s), have often (and rightfully) been placed at the heart of the innovation process, where they are forced to address many non-technical challenges (Hughes, 1987; Law, 1987b). Some of these challenges are associated with the creation of new organisations and institutions that can support the emergence of a capital goods industry with a capacity to produce innovative new products and services (Rosenberg, 1976; Nelson, 1994).

Over the past few decades or so, innovation and economic development have been increasingly associated with achieving sustainable growth in the face of climate change and other environmental threats. The contemporary climate challenge has been defined as limiting the Earth's temperature increase to two degrees Celsius over the long-term. According to the best available knowledge today, this would require reducing green house gas emissions in the developed world by 30-40 percent from 1990 levels by 2020, and by 80 percent from 1990 levels by 2050 (IPCC, 2007; Stern, 2007).[1]

"Limiting temperature rise to 2˚C requires a low carbon revolution"
(IEA, 2009, p. 45)

Such a radical change in emission levels would have a significant impact on all fossil-based, energy-intensive activities, and require profound socio-technical changes to current energy

[1] Current policies and the pace of economic development will lead to CO_2 concentrations in the atmosphere of 1,000 ppm. The risk that human activities result in an increase of the global average temperature of more than six degrees Celsius is, in such a scenario, significant and would result in irreversible damage to the environment (IEA, 2009).

systems and consumption patterns. In this transformation, the mainly fossil-based energy system must be replaced by a wide range of carbon-neutral technologies. These technologies only exist on a very small scale today when compared to the global energy supply.

Hence, in order to create a sustainable global economy in the face of climate change, we not only need to develop the most environmentally friendly technologies possible, but also take actions to diffuse them widely on a global scale within the given time frame of less than four decades. This requires the formation of a wide range of capital goods industries capable of developing and delivering carbon-neutral technologies on a large scale.

This thesis sets out to analyse the role of the system builder in the emergence of an industry with the capacity to develop and diffuse such a technology: biomass gasification for the production of renewable transportation fuels and other chemicals. In addition, the thesis is concerned with identifying the challenges for policymakers and system builders interested in commercialising the process and, eventually, diffusing it widely.

The process of gasification refers to the thermal conversion of any carbon-based fuel to a gas with a usable heating value (Higman and van der Burgt, 2003). It has previously been developed as a technology almost exclusively based on fossil resources, and an industry with the capacity to build and operate gasification plants for electricity production, various chemicals, nitrogenous fertilisers and transportation fuels already exists. However, the technology is still immature with regard to using biomass as the feed-stock for advanced applications such as the production of transportation fuels and other chemicals.[2]

In total, 24 biomass gasification plants have been commissioned by European-based companies since the early-1980s.[3] The plants have been made operational for less complex applications such as lime kilns, boilers, gas engines and when the biomass is co-fired with coal. On the other hand, actors pursuing the technology have, so far, failed to deliver

[2] These fuels are distinctly different from first-generation fuels from food crops, produced through mechanical or biological processes. At times, the process of turning biomass to a liquid is referred to as BtL (biomass-to-liquid), and the fuels are commonly referred to as second-generation renewable transportation fuels or, alternatively, simply second-generation fuels.
[3] The plants refer to large demonstration and commercially operating plants. Hence, small-scale pilots and fixed-bed gasifiers are not included in the count.

biomass gasification systems for power generation through integrated gasification combined cycle (IGCC) technology, as well as for the production of second-generation renewable transportation fuels and other chemicals—all of which are more advanced applications. The market success of biomass gasification has, thus, so far been limited.

The rest of this chapter is structured as follows. The empirical and analytical points of departure for the thesis will be explained in Sections 1.1 and 1.2, respectively. The purpose and the structure of the thesis will be outlined in Section 1.3.

1.1 Empirical points of departure

The time frame for fostering new industries with the capacity to be innovative and diffuse a wide range of renewable energy technologies has, in recent years, gained an importance beyond achieving just long-term growth and economic development. For the first time, a relatively well-defined time frame has been established for when a wide range of renewable technologies must be able to make a significant contribution to the world's energy supply, instead of being marginally used as it is today. This thesis will illustrate that not only has it taken many decades to develop second-generation renewable transportation fuels, but also that the remaining challenges will be with us for many years to come.

In an ideal world, targets and policies would reflect the challenges ahead in limiting global warming to two degrees Celsius in order to avoid the risk of severe and irreversible impacts on the environment (IPCC, 2007). While it is encouraging that many influential political leaders recognise that climate change is caused by human activity and that it is one of the most important challenges for national and international policymaking (G8, 2009; Meinshausen et al., 2009), so far there is no binding, overall agreement on how this target should be reached.

For the European Union, green house gas (GHG) mitigation is mainly about limiting the emissions associated with energy use, which in 2008 accounted for approximately 80 percent of all GHG emissions (Eurostat, 2010b). Although the overall amount of GHG emissions has decreased by 11 percent between 1990 and 2008, emissions related to modes of transport have increased by approximately 24 percent since 1990,[4] and contributed to approximately 20 percent of total GHG emissions within the EU-27 in 2008 (Eurostat, 2010b). Hence, without reducing emissions from the transport sector, stringent GHG emissions targets in Europe will be difficult to meet.[5]

When prescribing policies for targets as ambitious as limiting climate change to two degrees Celsius, there are also other societal goals and interests that must be taken into consideration and balanced against each other. It is thus important to consider energy policies in Europe not only in relation to the climate change debate, but also in relation to the increasing focus on energy and job security, “peak oil”, as well as the associated and expected increase in the price of liquid fuels in the future.[6]

With regard to energy security, oil consumption in the USA, EU, China and Japan accounted for more than 56 percent of the global total, although the same countries only accounted for 15 percent of the production of oil in 2008 (BP, 2009). This makes these four high consumption countries/regions heavily dependent on imports and vulnerable to the actions of a few oil producing countries. As for peak oil, and based on a survey of recently published papers, there appears to be an increasing consensus amongst oil exploration experts that peak production will be reached in the near future (de Almeida and Silva, 2009). [7] In the long-term, ever-increasing demand and diminishing supply will inevitably drive up the price of oil and increase incentives to develop both fossil-based and renewable unconventional liquid fuel sources.

Fossil alternative liquids such as extra heavy oils, bitumen, oil shales, gas-to-liquid (GtL) and coal-to-liquid (CtL) conversion are abundant in supply, easy to scale up production-wise, and

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[4] GHG emissions from the transportation sector continue to increase, while emissions from the energy sector (not including transportation) have started to decline from high levels (60 percent of the total emissions 2007) (Eurostat, 2007, 2009).

[5] Increased use of public transportation, new habits in combination with more efficient engines and an electrification of the drive-train have the potential to substantially reduce the need for liquid fuels in the future, but not eliminate it completely. The challenge ahead can only be solved by simultaneous, and parallel development and diffusion of a wide range of measures.

[6] Liquids include not only oil but also renewable fuels and alternatives derived from fossil resources.

[7] Most of the uncertainty around the actual date of peak oil depends on the behaviour of Saudi Arabia. Its future production capacity is at present very uncertain; this number is absolutely critical for defining a more exact world peak oil date (de Almeida and Silva, 2009). However, the majority of the studies referred to in the paper indicate that peak oil could come as soon as around 2015.

generally cheaper to develop than renewable alternatives (IEA, 2008). Hence, without significant policy initiatives, it is primarily the fossil alternatives that will be developed and not the renewable ones. Consequently, the EIA (2007), IEA (2008), and Aleklett et al., (2010) estimate that by 2030 approximately 20-26 percent of world liquid fuels[8] will originate from fossil alternative sources which emit significantly more GHG emissions than conventional oil (IES JRC, 2007).

With EU Directive 2003/30/EC, which promotes the use of biofuels and other renewable fuels for use in transportation, a sizeable market has been created within the European Union for non-fossil alternatives (EC, 2003). The target set by the directive is that biofuels are to account for 5.75 percent share of all transportation fuels by 2010.[9] This was followed up in 2009 with a new directive, 2009/28/EC, that sets a binding 10 percent target for renewable energy, vis-à-vis the final amount of energy consumed for transportation purposes by 2020 (EC, 2009a).[10] The commercial availability of second-generation fuel has been identified as pivotal for realising this target and has become a priority (EC, 2009a).

So far, the directive on renewable transportation fuels has stimulated the production of the so-called first-generation biofuels, which are primarily derived from food crops such as corn, wheat, sugar cane and soya. This has resulted in a public debate around the social and environmental desirability of the production and use of biofuels, not least in relation to its impact on food production and biodiversity, as well as its real CO_2 savings potential (JRC, 2008). Some of these objections have been taking into consideration when drafting the new directive, 2009/28/EC.

With regard to second-generation fuels, studies have illustrated that they have a CO_2-saving potential of approximately 90 percent, and that 45-70 percent of the energy content in

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[8] World liquids refer to the sum of conventional oil and unconventional liquids developed as a substitute for oil.

[9] This target will not be met since the share of biofuels in the transportation sector was only 3.3 percent in 2008 (Eurostat, 2010c).

[10] The target for renewable transportation fuels should be viewed in the light of the overall target of the EU to increase the use of renewable energy to 20 percent of total energy use in the EU-27, and cut CO_2 emissions by at least 20 percent by 2020, as compared to 1990 levels. It also involves improving energy efficiency by 20 percent by 2020 (EC, 2007). The directive states that the share of renewable energy in the transportation sector should be the same for all member states, since renewable transportation fuels can easily be traded. Meanwhile, the overall targets for renewable energy and emission reductions will be divided between the countries in accordance with their ability to comply (EC, 2008).

biomass can be converted into a usable fuel, which would be a significant improvement compared to first-generation biofuels based on food crops (IES JRC, 2007; RENEW, 2008; Thunman et al., 2008). Moreover, with gasification, a wide range of biomass can be used as feed-stocks. In the long run these may include low-cost waste streams. The total substitution potential of biomass gasification is, therefore, much higher than that of first-generation fuels.[11] However, the cost of production is considerably higher compared to first-generation fuels due to the high investment costs of plant construction (DENA, 2006; JRC, 2008).

The substitution potential of second-generation fuels based on the gasification of domestically produced biomass resources in Europe is difficult to assess for three main reasons. First, it depends on how much additional biomass can be produced and if, or when, lower grade biomass and waste sources can also be used for fuel production. Social and environmental aspects associated with increasing production are difficult to assess and make most estimates of biomass potential uncertain at best. It can, however, also be argued the increased use of biomass increases the potential, since actors discover new biomass resources to explore that had previously been unknown, underdeveloped and difficult to measure (Kåberger, 2009). Bearing these uncertainties in mind, the potential for increasing the supply of biomass in Europe has been assessed in several studies.

In RENEW (2008), the current and unused potential of biomass for energy purposes in Europe was estimated to be 95Mtoe. With improved agricultural practices, primarily in Eastern Europe, it was deemed possible to increase this amount to approximately 172Mtoe by 2020. Ericsson and Nilsson (2006) estimated the long-term European potential to be approximately 410Mtoe, but their study also included the potential of biomass resources in Ukraine and Belarus.

Second, assessing the substitution potential of second-generation fuels based on the gasification of biomass depends on what is perceived as a desirable allocation of biomass in the context of its other potential uses. Global system studies have concluded that the potential long-term supply of biomass is low compared to the required amount of climate-

[11] The RENEW report, conducted by advocates of biomass gasification, indicates that the substitution potential is 2.5 times that of first-generation biodiesel production. However, actual potential will vary significantly with different set-ups of the technical systems.

neutral energy in a world aiming at limiting global warming to an increase of two degrees Celsius from pre-industrial levels (Azar et al., 2003). Since biomass scarcity will be a major constraint, it has further been argued that biomass would be used most cost efficiently by substituting coal in electricity and heat production rather than for producing transportation fuels (Azar et al., 2003; Grahn, 2009; Hansson, 2009).

However, throughout this study the advocates of biomass gasification and liquefaction projects have emphasised that biomass is the only renewable feed-stock that can be used for producing renewable liquid fuels and chemicals, whereas for heat and electricity there are numerous cheap, renewable alternatives available[12] that do not include the use of biomass. Accordingly, it would also make sense to allocate parts of this resource for the production of transportation fuels and other chemicals.

Third, the potential of biomass depends on the thermal energy efficiency of turning biomass into fuel. In several of the current biomass gasification projects for the production of second-generation fuels, the so-called Fischer–Tropsch (FT) diesel is seen as a preferred fuel (see Chapter III). It is, however, a complex molecule that takes more energy to synthesise than, for example, methanol, methane or dimethyl ether (DME). Whilst the exact conversion efficiency of the different alternatives are difficult to estimate—since the processes have not been commercialised for biomass—different studies point to conversion rates in the range of 45-70 percent, depending on the type of processes and fuels used (Ekbom et al., 2003; Zwart et al., 2006a; IES JRC, 2007; RENEW, 2008; Thunman et al., 2008).

A simple example has been constructed to illustrate the impact of these three factors on the substitution potential of biomass (see Table 1.1). This is based on total EU-27 fuel consumption in 2007 (309Mtoe), which is held constant (Eurostat, 2010a). As mentioned above, current and unused biomass resources have been estimated as 95Mtoe (RENEW, 2008). It has been argued that by 2020 these resources could be increased to 170Mtoe and perhaps as high as 410Mtoe over the longer term (Ericsson and Nilsson, 2006; RENEW, 2008). A low and high allocation of overall biomass potential was set to 40 and 60 percent, whilst energy efficiency spans between 45 and 70 percent.

[12] Including wind, solar, hydro, and geothermal for electricity production and better utilisation of waste heat.

Table 1.1: Substitution potential based on current fuel consumption in the EU-27 (2008).

Biomass Potential (Mtoe)		**95**	**170**	**410**
Low energy efficiency (45%)	Low Allocation (40%)	6%	10%	24%
	High Allocation (60%)	11%	20%	48%
High energy efficiency (70%)	Low Allocation (40%)	9%	15%	37%
	High Allocation (60%)	13%	23%	56%

The result from this simple example illustrates that the potential to produce transportation fuels from future biomass resources is highly uncertain, since the substitution potential varies between 6 and 56 percent depending on the choices made (see Table 1). Consequently, for maximising the substitution potential it is important that the advocates of renewable transportation fuels act to increase the overall amount of biomass resources available for energy purposes, secures a large share of the total, and act to maximise the thermal conversion efficiency of turning biomass into a usable transportation fuels.

Although highly uncertain, it is not unrealistic to assume that 25 percent (77Mtoe) of current (2008) transportation fuel use could be substituted by domestically produced second-generation fuels in the long run (2030-2050). To realise such a market, investments in plant construction of approximately €150-300 billion will have to be made (Chapter III). The direct employment effect would be substantial in Europe, with approximately 250,000–300,000 people in biomass collection and plant operation, not including the employment associated with plant construction and the potential associated with an export market. In addition, if such a market can be realised, the EU would avoid oil imports of about $100 billion annually,[13] which results in very few jobs within the European Union (Chapter III). However, realising this potential requires the emergence of a new industry and a biofuel market that includes second-generation fuels.

The embryo of such an industry already exists and has a long and fascinating history. The first experiments with biomass gasification for the production of transportation fuels and other chemicals started around the time of the first oil crises. The actors involved in its development could draw extensively on the general development of fossil gasification and pyrolysis, which has been ongoing for the past 250 years, as well as the more recent

[13] 77Mtoe is approximately 566 million barrels of oil equivalent (1toe=7.33boe). I assume a nominal oil price of $190/bbl in accordance with EIA (2009, p.65) high price scenario.

development of fluidised bed combustion of biomass. Since the 1970s, various actions and events ultimately resulted in the formation of nine major gasification demonstration projects in four European countries: Austria, Germany, Sweden, and Finland.

If pursued successfully, each of these nine projects may significantly contribute to the formation of a capital goods industry that can deliver the production capacity needed to reach current EU targets and beyond. The analytical points of departure for studying the emergence of such an industry will now be provided.

1.2 Analytical points of departure

The theoretical strand of evolutionary economics has developed as a reaction to the dominance and shortcomings of neo-classical economic theory. From the outset, it has been based on the ideas of Marx (1887; 1888) and Schumpeter (1934; 1942) with regard to innovation and economic development (Nelson and Winter, 1982; Dosi and Nelson, 1994). Schumpeter (1934) describes major and radical innovations as the central process for driving economic development.[14] Such innovations induce disruptive technical, institutional and organisational changes that constantly move the economy away from equilibrium (Rosenberg, 1976). Evolutionary economics, thus, has a very different point of departure than neo-classical theory, which deals with how markets operate under conditions of equilibrium. In this respect, neo-classical theory has been described as " … an inappropriate tool to analyze and prescribe policies that will induce development." (North, 1994, p.359).[15]

Based on evolutionary, institutional and industrial economics, an additional body of literature has evolved since the mid-1990s. It deals specifically with analysing the performance and dynamics of various systems of innovation. The basic question of the research has been why some countries have been much better at promoting, developing and profiting from innovation than others. The National Systems of Innovation (NSI) framework

[14] Schumpeter doesn't use the term "major innovations", but it is major innovations such as electricity production, railways, automobiles, airplanes, etc. that involve the creation of the new production systems that he refers to. The point here is not to come up with some sort of classification of innovations and argue that biomass gasification is of a certain type. The point is that biomass gasification is a major innovation that would result in technical, organisational and institutional change, if diffused on a large scale for the production of renewable transportation fuels and other chemicals, and that this would require the emergence of an industry with such a production capacity.

[15] Using the same line of argument, neo-classic economics can also be assessed as inappropriate for analysing and prescribing policies that will stimulate innovation, technical change and diffusion.

(Freeman, 1987; Lundvall, 1992) has dominated (Carlsson, 2006, 2007), but similar systems have been defined and analysed on regional (RSI), sectoral (SSI) and technological (TIS) levels.

All four innovation system perspectives pay considerable attention to the relationship between technology, organisations, networks and institutions in the innovation process. According to North (1994), the institutions define the rules of the market. The alignment between the new technologies, organisations and the institutional framework is a key determinant for the successful introduction of new innovations. New institutions are, however, not created to be socially efficient, but rather " … created to serve the interests of those with the bargaining power to create new rules" (North, 1994, p. 361). Mature and large technical systems—such as the energy and transportation systems—are dominated by a few large incumbent actors with considerable bargaining power (Hughes, 1987; Froggatt, 2003; Hellsmark, 2005). The process of institutional alignment is, therefore, often a painful one marked by great uncertainty, conflicting interests between advocates of the old and new technologies and between proponents of various designs alternatives of the new technologies (Nelson, 1994; Utterback, 1994; Meijer, 2008). Without "re-alignment", it would be impossible for new technological systems to reach what Hughes (1987) calls a "momentum of its own" and move into a phase marked by rapid growth.

Studying this painstaking process of alignment involves unfolding the evolutionary interactions between institutions, technology, organisations, and their entrepreneurs. "It is the interaction between institutions and organizations that shapes the evolution of an economy. If institutions are the rules of the game, organizations and their entrepreneurs are the players" (North 1994, p.361)

The principal actors in the innovation process are the entrepreneurs, who are often associated with strong, visionary individuals. However, entrepreneurship can also be the result of a collective effort, supported by an infrastructure that makes it possible (Van de Ven and Garud, 1989; Van de Ven, 1993; Summerton, 1994; Van de Ven, 2005). At the beginning of the "formative phase" (Jacobsson and Bergek, 2004), these individuals are few in number, and they engage in system building activities that go beyond conventional technology development (Hughes, 1987; Law, 1987b; Hellsmark and Jacobsson, 2009). In this thesis, they are referred to as system builders instead of entrepreneurs.[16]

In this thesis, I will depart from the technological innovation systems (TIS) framework since it provides the tools necessary for analysing the emergence of an industry with the capacity to realise the potential of a specific technological field such as biomass gasification. From the outset, a TIS was defined as " ... a network of agents interacting in a specific economic/industrial area under a particular institutional structure or set of infrastructures and involved in the generation, diffusion, and utilization of technology. Technological systems are defined in terms of knowledge/competence flows rather than flows of ordinary goods and services." (Carlsson and Stankiewicz, 1991, p. 111).

The TIS framework has recently been used as an analytical tool for studying system dynamics in the emergence of new technological areas within the energy sector.[17] For example, it has been used to analyse the emergence of new power production technologies based on wind, solar and biomass but also other technological areas such as biofuels, biomass digestion, gasified biomass, fuel cells and nanotechnology (Bergek, 2002; Jacobsson et al., 2004; Negro et al., 2007; Hillman and Sandén, 2008; Jacobsson, 2008; Negro et al., 2008; Nygaard, 2008; Perez Vico and Sandgren, 2008; Suurs, 2009).

Throughout the thesis, I will focus on the formative phase of a system's development, which extends from when the first actors—system builders—try to commercialise an invention, to the time when the new system[18] reaches a "momentum of its own" and moves into a "growth phase" marked by rapid market expansion (Hughes, 1987; Jacobsson and Bergek, 2004). The formative phase is dominated by great technical, organisational, market and institutional uncertainties that have to be resolved before the TIS can move into a growth phase. For most major innovations, it takes a long time to resolve these uncertainties and

[16] The concept of entrepreneurs is primarily associated with starting companies, while the system builders referred to in this study may also focus on creating conditions that enable others to start new firms, or for incumbents to develop new business opportunities.
[17] The development of the framework actually started in the early-1990s within the context of Sweden's Technological Systems programme led by Professor Bo Carlsson (1995, 1997).
[18] In this thesis, I view the development of biomass gasification technology as an emerging knowledge field, which consists of new combinations of already existing fields rather than as a "product innovation". The distinctions will be further explained in Chapter II, in which the theoretical framework will be specified.

the outcome is highly uncertain. The time frame of the formative phase is often hugely underestimated; even if successful, it can extend to several decades (Utterback, 1994; Grubler, 1998; Lindmark, 2002; Chesbrough, 2003; Jacobsson and Bergek, 2004; Suurs, 2009; Wilson, 2009).

Recent developments of the perspective (Hekkert et al., 2007; Bergek et al., 2008a; Bergek et al., 2008b; Bergek et al., 2008c; Markard and Truffer, 2008) contribute to an elevated understanding of the dynamics involving the interaction between the actors, other structural entities of the system and exogenous factors. As the system evolves, these interactions induce certain emergent properties (or attributes) of the system. These properties may vary significantly over time, across different TISs, as well across a given TIS in different countries. Various sets of key properties, "functions" of an innovation system, have been elaborated on since Johnson and Jacobsson (2001) and Bergek (2002).[19]

The dynamics of a TIS can, thus, be analysed both in structural and functional terms. Based on such an analysis, the strengths and weaknesses of a system can be assessed and useful conclusions can be derived both for public and private policymakers interested in strengthening it in relation to competing TISs (Hekkert et al., 2007; Bergek et al., 2008b; Suurs, 2009).

In this thesis, I set out to contribute to the TIS framework by strengthening the analytical link between the individual actor (or network of actors) and the dynamics of a TIS. This will be done by further conceptualising the role of the "system builder" (Hughes, 1987) as a key actor, or network of actors, in the formation of new industries who is equipped with a "transformative capacity" (Giddens, 1984a). The extent and limits of the system builders' transformative capacity will be assessed from a technological innovation systems perspective, that is by the system builders' ability to create and strengthen the structure as well as the functions of the TIS.

[19] Exactly which key properties that should be considered have evolved over time, and there are some slight differences between different papers and authors.

1.3 Purpose and outline of the thesis

The overall purpose of this thesis is to analyse the role of the system builders in the emergence of an industry with the capacity to realise the potential of gasified biomass for the production of second-generation transportation fuels and other chemicals within the European Union. This overall purpose will be broken down into a set of research questions in Chapter II.

The thesis is divided into three main parts and twelve chapters. Part I includes this introduction (Chapter I), as well as the analytical framework (Chapter II). Chapter III outlines the evolution of gasification technologies and analyses the interrelated knowledge fields necessary for turning biomass into various products such as heat, electricity and transportation fuels. It also outlines the past and present biomass gasification market, as well as the current status of nine major projects in Austria, Germany, Sweden, and Finland undertaken by actors that hope to develop and capture the potential market for second-generation renewable transportation fuels. The methods used for conducting the study are presented in Chapter IV.

The second part of the thesis, Chapters V-VIII, analyses the evolution of biomass gasification leading up to the current main projects in each of the four case study countries. These chapters provided detailed case studies of the dynamics of the respective technological innovation system.

The third and final part of the thesis consists of four chapters. In Chapter IX, a cross-country analysis is presented. It is followed by an analysis of contributions to system dynamics by other actors and elements of the structure than the system builders (Chapter X). Chapter XI provides an analysis of the main policy options for completing the formative phase and moving the TIS into a growth phase. The thesis is finalised with Chapter XII, which summarises the main contributions and draws implications for system builders, policymakers and for future research.

Chapter II
The emergence of new industries[20]

"Human history is created by intentional activities, but is not an intended project."

(Giddens, 1984b, p.27)

Technical change provides an encompassing stimulus to the economy and adds to the quality of our everyday lives. Ever since Marx (1887), Schumpeter (1934; 1942) and Hughes (1979; 1983; 1987, 1989), innovation, entrepreneurship and the emergence of new industries have been identified as main drivers of economic growth, where entrepreneurs, or system builders, are seen as key actors in the creation of such industries.

Innovation is invention implemented and taken to market (Chesbrough, 2003). The process of biomass gasification for the production of second-generation fuels and other chemicals is an invention based on new combinations of existing knowledge that at a first glance may appear rather simple.[21] The combinations, however, give rise to a knowledge field and specific technical challenges, which should not be underestimated. These will be outlined in Chapter III.

The production of second-generation fuels and other chemicals based on biomass gasification has the potential to become *a major innovation:* if implemented, it will create a new industry and influence current social practices. Other examples of major innovations that have given rise to new industries and influenced social practices are the production of electricity, the telephone, the automobile, the personal computer, and the Internet (cf. Chapter I). For example, according to Marx (1887), Schumpeter (1934; 1942) and Rosenberg (1976), such major innovations change not only the technology base and social practices, but also the organisational and institutional structure of society.

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[20] Parts of this chapter draw on Hellsmark and Jacobsson (2009).

[21] In some areas, biomass gasification is already an innovation because it is used commercially in simple applications. Realising biomass gasification for more advanced applications may appear to be a straight-forward task, as experience and knowledge can be combined from these simple biomass applications, from biomass combustion and from the commercial use of coal gasification (se Chapter III).

Major innovations implicate a technological, organisational and institutional change along an entire value chain, where a range of complementary products must be changed or created. Hence, in order to industrialise a new knowledge field, an industry needs to develop with the capacity to produce required capital goods (i.e., machinery and equipment) according to certain specifications along the entire value chain. Consequently, the emergence of a capital goods industry, with such a capacity, is identified as key factor in the innovation and diffusion process (Rosenberg, 1976).

The challenge of transforming the energy sector from predominantly being based on fossil energy sources is one that involves the development, production and diffusion of new equipment for, for example, renewable power generation, increasing energy efficiency, and production of renewable transportation fuels and other chemicals. It requires, therefore, the emergence of an industry with the capacity to supply a broad range of capital goods on a global scale.

As already mentioned in Chapter I, the time frame during which such a capacity is developed in an embryonic form has been defined as the formative phase of a TIS (technological innovation system) (Jacobsson and Bergek, 2004). It is dominated by technical, organisational and institutional uncertainties that may take many decades to resolve and where the outcome of the process is highly uncertain.[22] The purpose of this chapter is to outline a framework that is suitable for analysing the process by which an industry emerges with the capacity to manufacture and diffuse the capital goods required for realising the potential of a new knowledge field.

The process of innovation and industrial transformation has been the main topic of scholars from various disciplines for decades. To fulfil the above-mentioned purpose, I have chosen to depart from the technological innovation system framework. I will, however, also draw upon other innovation system frameworks and from insights in industrial dynamics, evolutionary and institutional economics, science and technology studies, as well as sociology.

[22] Hence, for mitigating climate change, the capacity of the capital goods industry must already exist, or be developed within the next few years for large-scale diffusion to be possible within the given time frame.

The chapter is organised in the following manner. First, three complementary socio-technical system perspectives will be introduced. Based on the national, sectoral and technological innovation systems frameworks, the analytical scope of the thesis is outlined and initial steps towards delineating the system are taken. In the second, third and fourth sections, the dynamics of an emerging TIS will be conceptualised. In the fifth section, specific characteristics of system dynamics with regard to uncertainties and system weaknesses in the formative phase will be addressed. This section also includes an analysis of the role of system builders and policymakers in identifying and addressing such system weaknesses. In the sixth and final section, the purpose of the thesis will be restated and broken down into a set of research questions.

2.1 Systems of innovation and the emergence of new industries

Innovation systems studies have become an important tool for analysing the emergence of innovations, new industries and economic growth (Carlsson, 2006). These studies depart from evolutionary economics but have a history of drawing from other fields as well. In this first section of Chapter II, three such innovation systems frameworks will be outlined, namely National Systems of Innovation (NSI), Sectoral Systems of Innovation (SSI) and Technological Innovation Systems (TIS).

A system is in the broadest possible definition "anything that is not chaos" (Boulding, 1985). "Somewhat more specifically, a system is constituted by a number of elements and by the relationships between these elements" (Lundvall, 1992, p.2). These systems do **not** necessarily exist "out-there" in a real sense, but they are used as analytical constructs to shed light on different aspects of the innovation process.

The first system of innovation (SI) to be elaborated on was the National Systems of Innovation (Freeman, 1987; Lundvall, 1992). Lundvall (1992, p. 2) first defined a SI and then a NSI as " ... constituted by elements and relationships which interact in the production, diffusion and use of new, and economically useful, knowledge and that a national system encompasses elements and relationships, either located within or rooted inside the borders of a nation state."

A NSI, thus, delineates the system in spatial terms.[23] A system may be based on a nation as the name suggest but also on a larger region such as the European Union or a smaller region such as Malmö-Copenhagen or Baden-Württemberg (Regional Systems of Innovation, Cooke, 1992). Policy is also formulated on both national and regional levels with the objective of stimulating innovation, job creation and overall economic growth. It is likely that the interplay between these different policy levels strongly influences the dynamics of a SI, as well as the emergence of new industries with innovative capabilities.[24]

However, depending on the purpose of the inquiry, the definition of innovation systems may not be based on spatially defined boundaries. It has been proposed that different sectors develop a specific logic and relations between elements with respect to technological innovation. Malerba (2002) argued that an SSI[25] framework can be a useful tool for analysing these inter-sectoral differences in patterns of innovation.

Sectoral systems of innovation studies have illustrated that the sources and patterns of innovation vary greatly between different sectors.[26] They also illustrate that fruitful relationships exist between small innovative firms and large incumbents, wherein both types of firms may profit from each other and where they fulfil distinctly different roles in the innovation process. For example, the role of the small entrepreneurial firm may be to explore new ideas and combine knowledge from various sectors into new profitable businesses, while the incumbents may take on the role of further developing these new businesses on the global market (Pavitt, 1984; Malerba and Orsenigo, 1996; Tushman and O'Reilly, 1997; Malerba, 2002; Chesbrough, 2003).

Patterns of innovation differ between sectors due to shared cognitive routines in engineering communities (Nelson and Winter, 1982), regulations and standards that may be

[23] The NSI is a concept related to how Porter describes the competitiveness of nations and the importance of clusters for regional development (Porter, 1990b, a).
[24] In this study, I have limited the analysis to four countries: Austria, Germany, Sweden and Finland. However, policy of importance is also formulated on a local, regional and EU level. All four levels formulate policy that has the potential to greatly impact the emergence of new industries in the field of biomass gasification.
[25] A sectoral system of innovation has been defined as " ... a set of new and established products for specific uses and the set of agents carrying out market and non-market interactions for the creation, production and sale of those products." (Malerba, 2002, p. 248)
[26] In the current case of biomass gasification in Sweden, Finland, Austria, and Germany, there are numerous sectors that influence the dynamics of the system (see Chapter III).

sector specific, or sunk investments in knowledge, technological artifacts and infrastructures (Tushman and Anderson, 1986; Christensen, 1997). These patterns are reinforced by scientists, policymakers, users, and special interest groups affiliated with a certain sector. They give a direction to what can be defined as “normal” problem solving activities within a specific “technological paradigm”, selecting which problems to solve (Dosi, 1982; Geels and Schot, 2007).[27]

For the given purpose, it was proposed (in Chapter I) that a technological innovation systems framework would be an advantageous starting point. Based on recent development, this system has been defined as “ … a set of networks of actors and institutions that jointly interact in a specific technological field and contribute to the generation, diffusion and utilization of variants of a new technology and/or new product” (Markard and Truffer, 2008, p. 611).[28]

The dynamics involved in the formation of a new knowledge field includes the interaction, collaboration and competition between multiple actors from various sectors, new start-ups, established firms, university departments, institutes, etc. These actions and interactions give rise to a variety of new technological trajectories ($Tr_{1..3}$) within a given knowledge field (TIS_1) and competing knowledge fields (TIS_2, $Tr_{1..2}$), see Figure 2.1. The various new trajectories are an outcome of actors interpreting opportunities differently in relation to their capabilities, previous experiences, investments, and strategic goals.

The actors are constantly experimenting and elaborating on the knowledge field of the TIS by exploring various new applications, which in turn may also create a capacity to explore yet further types of applications (Rosenberg, 1976). The field constantly undergoes an evolution during which the content, extent and depth of the knowledge field changes. It has previously been argued that the technology base in a TIS can be described in terms of

[27] In the literature, the broader forces in play have been described as “socio-technical regimes”, as well as sectoral systems of innovation.

[28] Due to these recent developments, I have chosen not to use the commonly used definition of a TIS as “ ... a network of agents interacting in a specific economic/industrial area under a particular institutional structure or set of infrastructures and involved in the generation, diffusion, and utilization of technology. Technology systems are defined in terms of knowledge/competence flows rather than flows of ordinary goods and services.” (Carlsson and Stankiewicz, 1991, p.111).

“design space” (this concept will be further elaborated on in Section 2.2.1) (Carlsson et al., 2002a).

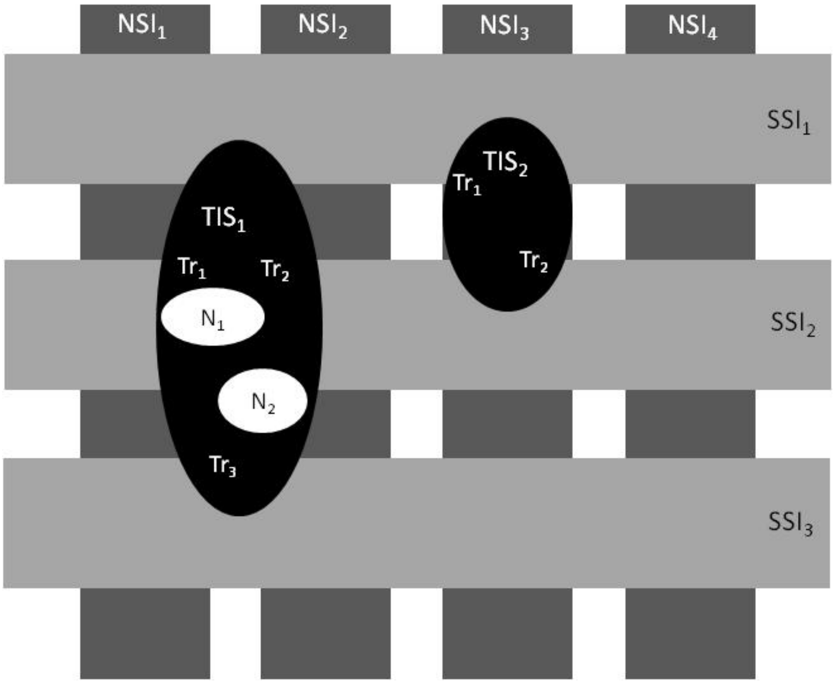

Figure 2.1: Delineation of two emerging TISs in terms of their national and sectoral boundaries, also illustrating the existence of various trajectories (Tr) and niche markets (N). Based on Markard and Truffer (2008).

Since a TIS can transcend national borders, it does not have to be delineated in spatial terms. However, in the formative phase, the actors within a given TIS are few and they may be found in even fewer countries. In these countries, the TIS may be under the influence of a limited number of SSI that vary between countries. Therefore, the concepts of NSI and SSI can also be used for delineating an emerging TIS (see Figure 2.1) (Markard and Truffer, 2008). The system of biomass gasification is delineated in Chapter IV.

In summary, it has been argued here that an innovation system perspective is an appropriate framework for analysing the emergence of new industries. These arguments will be further strengthened and the complete dynamics of the emergence of a TIS will be conceptualised in the following sections.

2.2 The structural evolution of a TIS in the formative phase

A TIS is composed of the following structural elements: technology, actors, institutions and networks (see Table 2.1). In this section, these structural elements will be defined.

Table 2.1: The structural elements of a TIS.

Structural Elements	**Definition**
Technology	is made up of artefacts (tools, plants, machinery), coded knowledge (patents, drawings, etc.), and knowledge embodied in, for example, engineers and scientists.
Actors	are individuals, private and public firms, and organisations that perform a task that contributes to the development of the technological field.
Networks	are defined by the relationship between the different actors in the system and include both learning and political networks.[29]
Institutions	are sets of norms, common habits, routines, established practices, rules or laws that regulate the relationships and interactions between individuals and firms.

Source: Bergek et al. (2008b).

2.2.1 Technology

Technology is defined here in line with Carlson et al.'s definition (2002a, p.13) " ... the sum total of intellectual resources necessary for the production and distribution of goods and services", but with a greater emphasis on artefacts. However, the essence of technology is still knowledge. This knowledge is not only embedded in the artefacts themselves, drawings and patents, but also in the operational experience of the personnel handling of the technology and in the engineers that design it (Layton, 1974).

Carlsson et al. (2002a, p.13) refer to the technology base of a TIS as " ... a set of combinatorial design spaces formed by *clusters of complementary technological capabilities* ... ". These spaces undergo constant evolution and are shaped by, for example, the addition of new capabilities and the accumulation of application-specific know-how. As the design spaces expand, they give rise to new technological and business opportunities. Indeed, in the " … long run, the boundaries and characteristics of technological systems will reflect the structure and character of design spaces" (Carlsson et al., 2002a, p.14).

[29] It may, sometimes, also be useful to include networks between artefacts.

Technology is seen here as both a structural element and an output of the system.[30] It is brought into the TIS with the entering actors based on their previous experiences and by borrowing or copying from other potentially useful knowledge fields. It is also produced in the system as the actors learn more of the combinatorial opportunities and characters of the various design spaces.

What is here referred to as the design space of biomass gasification is made up of sub-sets of design spaces formed by more narrow complementary technological capabilities. For the TIS to evolve, chains of these technological capabilities must be created to form complete value chains. Hence, for producing a new type of transportation fuel from a specific type of biomass, complementary technological capabilities may have to be created (extending the aggregated design space of the TIS) in terms of biomass production methods, collection, pre-treatment, conversion, and turning it into the desired fuel. Further capabilities may also have to be created for distribution and use of the new fuel depending on the types of vehicles and potential end-users.

2.2.2 Actors

The firm is usually seen as a key actor in any innovation system and is normally the principal unit of analysis in evolutionary economics (Nelson, 1995b). However, the term “actor” also refers to individuals and different types of organisations, including industry associations and non-professional organisations that perform both market and non-market interactions along the entire value chain. The actors included in the system are restricted to those that dedicate resources to develop the field and exclude those entities that neglect the new technology or oppose it.

These actors “ ... operate with different knowledge base and under different assumption concerning technology, markets etc.” (Carlsson and Stankiewicz, 1991, p. 100). Consequently, they also react to and perceive opportunities differently from one another, even if they have equal access to information.

[30] In some earlier work on TIS, technology was not explicitly treated as a part of the structure.

Actors may thus react differently to opportunities depending on which SSI or technological paradigm they may be associated with (Dosi, 1982; Nelson and Winter, 1982; Geels and Schot, 2007). Established actors with deeply rooted values and sets of well developed core capabilities within a certain paradigm run the risk of suffering from various cognitive inertia and lock-in effects, which may hinder them from discovering and acting upon new opportunities (Arthur, 1989; Leonard-Barton, 1992; Tripsas and Gavetti, 2000). This is also why competence destroying innovations are usually carried out by new firms such as start-ups, spin-offs or entrants from related industries, and not by the incumbents (Tushman and Anderson, 1986).

However, we also know that incumbent firms are under pressure to be innovative outside their core areas. Even if these firms are faced with high development costs and the certainty that most major innovations will fail, some innovations will be successful and these may be necessary for the long-term survival of the firm (Chesbrough, 2003).[31]

"Most innovation fail. Firms that do not innovate die."

(Chesbrough, 2003, p. xvii)

In previous literature, the most important actors in the early phase of a TIS have been described as the prime movers, and can be entirely new firms or incumbents diversifying from related industries (Jacobsson and Johnson, 2000; Johnson and Jacobsson, 2001; Jacobsson et al., 2004).

[31] Some incumbents are better than others with regard to profiting from major innovations, regardless of whether the development of these innovations occurs through strategic alliances with partners, acquisitions of new entrants or internal development. These firms have been described as "multi-technological", which enable them to absorb new knowledge, develop new opportunities and profit from achievements in various unrelated knowledge areas (Granstrand et al., 1997). This ability to innovate has also been described as the firm having a set of "dynamic capabilities", or it being "ambidextrous", in the sense that they can profit from the existing business while developing new opportunities that pose a threat to the existing one (Teece et al., 1997; Tushman and O'Reilly, 1997). However, being ambidextrous, or having developed such dynamic capabilities, does not imply that the firms are free from their previous histories. On the contrary, the concept of dynamic capabilities has been defined as " ... the firm's ability to integrate, build and reconfigure internal and external competences ... and reflect an organization's ability to achieve new and innovative forms ... given path dependencies and market positions …" (Teece et al., 1997, p.516).

The prime movers not only bring knowledge, capital and other resources, but also play a role in attracting further actors with additional resources. Such new entrants experiment with new combinations, become specialist suppliers or develop new applications. They also ensure that a " … division of labour is formed and further knowledge formation is stimulated by specialization and accumulated experience (e.g. Smith, 1776; Rosenberg, 1976)." (Bergek et al., 2010a, p. 81).

In this thesis, prime movers are conceptualised as system builders, and they will be argued to be of particular importance as they pursue specific and "intentional activities" that clearly contribute to developing the system, or influence the direction of its evolution (Giddens, 1984a; Hughes, 1987; Summerton, 1994). This important role and capabilities of the system builder is elaborated on in Section 2.5.

However, the actors in the system do not necessarily work towards the same goal, and if they do, they may be in stark conflict with each other as to the "best" way to get there. These conflicts may be so poisonous that any collaboration and intentional interaction between them may be impossible. Still, these actors can, from our point of view, be part of the same emerging system of innovation. Therefore, the general direction of the TIS is far from directed, or orchestrated, by a certain set of actors but is rather largely an unintended outcome of the evolutionary process.

Nevertheless, there are often powerful actors or constellations of actors acting in alliances. An alliance is defined here, in accordance with Linnarsson (2005, p. 17), as:

" ... any voluntarily initiated cooperative agreement between two or more independent firms [or other organisation] that share compatible goals involving the exchange, sharing or co-development, of products, technologies or services."

These alliances can be organised into anything from formal joint ventures to informal cooperative ventures. The definition is introduced as a complement to "networks" as a means of distinguishing between more or less purposeful relationships.

2.2.3 Networks

With the entry of actors in the TIS, various types of networks can be formed. Networks are a third form of organisation (adding to the hierarchical structure of a firm and markets) in which information, knowledge and values[32] are interchanged (Carlsson and Stankiewicz, 1991, p.103). Well-developed networks become increasingly important with more complex tasks and in situations where the future market requirements on the actor are both unknown and unpredictable.

In the case of a formation of a TIS, it is fundamentally important to form knowledge networks and political networks. In knowledge networks, new ideas are elaborated on and new relationships are made. They also serve an important function of legitimising a new field by providing credible system studies in terms of the desirability of the new technology (Suurs, 2009), and can provide a base for creating political networks, or advocacy coalitions, with the objective of increasing the stability of the field by creating common standards and favourable framework conditions (Van de Ven, 2005). In a given TIS, there may be several advocacy coalitions, where each is typically associated with a specific technological trajectory. They consist of a range of actors with shared beliefs and compete to influence policy in line with these beliefs (Smith, 2000a). However, the raging conflicts that characterise the early phase of a TIS typically undermine efforts to form advocacy coalitions and, therefore, the possibility of institutional alignment.

2.2.4 Institutions

Institutions have been described as setting the rules of the game (North, 1990, 2005), and defined as "sets of common habits, routines, established practices, rules or laws that regulate the relations and interactions between individuals and groups" (Edquist and Johnson, 1997, p. 220).

Institutions refer to both "hard" rule-based forms such as laws and regulations, as well as "soft" aspects in terms of informal rules, norms, culture, and cognition. Scott (2008) identifies three types of rules: a) regulative rules such as regulations, standards, laws; b)

[32] Such values may, for example, be what the actors may regard as desirable images or expectations about the future (Jacobsson, 2008).

normative rules such as values, behavioural norms; and c) cognitive rules such as belief systems, agendas, guiding principles, etc. The rules are created, reproduced and changed through human actions and activities. Yet, these actions are, in turn, both constrained and enabled by the rules (duality of structure) (Giddens, 1984a).

Therefore, actors should not be seen as mere "cultural dopes", in the sense that they are only constrained by the rules. On the contrary, they " ... use rules to interpret the world, make sense and come to decisions" (Geels and Schot, 2007, p. 403). The rules enable action (Giddens, 1984a).

New institutions are not created to be socially efficient but are rather " … created to serve the interests of those with the bargaining power to create new rules" (North 1994, p. 361). With the emergence of a new TIS, the struggle over defining the institutional order gives rise to three dominant conflicts. The first has already been touched on and plays out between groups of advocates within a given TIS. It involves their internal struggle to align the framework to a particular set of beliefs and technical solutions. The second conflict occurs within incumbent firms when they enter a new TIS, as they are forced to balance between preserving the existing rule structure, which is necessary to keep the existing business, and acting to align the institutional framework to the new knowledge field. The third conflict plays out between the advocates of the emerging TIS and competing mature or other emerging TIS.

In conclusion, the formation of a new TIS involves four structural processes, wherein the system builders are the primary agent: accumulation of knowledge and artefacts, entry of firms and other organisations, formation of alliances and networks, and institutional alignment. These structural processes are mutually interdependent and intertwined with one another (Hughes, 1987). If a component is added or removed, it is likely to induce changes in other components, triggering a set of actions and reactions that may either propel the system forward or break it down (Carlsson et al., 2002b). Therefore, the formation of a TIS is a process of re-configuring, as the components co-evolve in an often painful process marked with great uncertainty (Nelson, 1994, 1995a; Hellsmark, 2005; Meijer, 2008; Nygaard, 2008).

2.3 Functions in a technological innovation system

Analysing the dynamics and interdependencies of the structural elements as they emerge in a given TIS is, of course, possible to do and is often done (see Klein Woolthuis et al. (2005) for an overview). However, the explanation of what drives this dynamic or what obstructs it is often done in an ad hoc manner. In order to understand the causal mechanisms in the dynamics of a specific TIS, it has been suggested that a structural analysis needs to be supplemented with an analysis of a set of key innovation and diffusion related processes (Bergek et al., 2008b). These processes are labelled "functions" (see Table 2.2).

By separating structures and functions, it becomes possible to assess what actually "happens" and what is being " ... achieved in the system rather than on the dynamics in terms of the structural [elements] only" (Bergek et al., 2008b, p.409). It then becomes possible to assess the positive or negative impact of particular structural elements, or combination of elements, on a set of key innovation and diffusion processes (Bergek et al., 2008b). Exactly which key process should be included in the analysis and how they should be defined has evolved over time. Arguably, which functions to be included can be somewhat flexible, depending on the purpose of the inquiry, the technological field in question and its context.

In this thesis, the point of departure is the seven functions described in Bergek (2008b). However, the function of *materialisation*, specified in Bergek et al. (2008c), is added since it is identified as particularly important in this study (see Table 2.2 for a summary of the different functions). The following sections will briefly describe each function, including some examples of how a stronger function contributes by building and strengthening the structure, as well as other functions. In the final part of the section, a somewhat extended analysis will be presented on how the various functions relate to each another from a epistemological perspective.

Table 2.2: Eight functions of a TIS.

Functions	**... is the process of strengthening:**
Knowledge development and diffusion ...	the breadth and depth of the knowledge base and how that knowledge is developed, diffused and combined in the system.
Influence on the direction of search ...	the incentives and/or pressures for organisations to enter the technological field. These may come in the form of visions, expectations of growth potential, regulation and policy, articulation of demand from leading customers, technical bottlenecks, crises in current business, etc. In a very early phase, it includes how prime movers (system builders) manage to define the technological opportunity and make it attractive for other actors to enter and further develop the field.
Legitimation ...	the social acceptance and compliance with relevant institutions. Legitimacy is not given but is formed through conscious actions by organisations and individuals.
Resource mobilisation ...	the extent to which actors within the TIS are able to mobilise human and financial capital, as well as complementary assets such as complementary products, services, network infrastructure, etc.
Entrepreneurial experimentation ...	the testing of new technologies, applications and markets whereby new opportunities are created and a learning process is unfolded. This includes the development and investments in artefacts such as products, production plants and physical infrastructure (i.e., the materialisation of new technology).
Materialisation ...	the development and investment in artefacts such as products, production plants and physical infrastructure.
Market formation ...	the factors driving market formation. These include the articulation of demand from customers, institutional change, and changes in price/performance. Market formation often runs through various stages (i.e., “nursing” or niche markets), in the form of demonstration projects, bridging markets and eventually mass markets.
Development of positive externalities ...	the collective dimension of the innovation and diffusion process (i.e., how investments by one firm may benefit other firms “free of charge”). It also indicates the dynamics of the system since externalities magnify the strength of the other functions.

Source: Bergek et al. (2008b; 2008c).

2.3.1 Knowledge development and diffusion

The function of *knowledge development and diffusion* refers to the process of strengthening the breadth and depth of the knowledge base and how that knowledge is developed, diffused and combined in the system (Bergek et al., 2008b).

This function is “... normally placed at the heart of a TIS ... ” since it is concerned with the evolution of the knowledge base in the TIS and is intrinsically associated with how the actors learn (Bergek et al., 2008b, p. 414). Learning—the acquisition of knowledge—is the most fundamental aspect of the innovation process and understanding how the actors learn about the new technology should, therefore, be the focus of the analysis of an emerging TIS (Lundvall, 1992).

Knowledge is here divided into two well known and widely recognised epistemologically distinct categories "knowing about" and "knowing how" (Grant, 1996). Knowing about is an explicit type of knowledge that relatively easily can be codified and made transferable between humans as information across time and space. "This ease of communication .. [is a] .. fundamental property ... " of the "knowing about" type of knowledge (Grant, 1996, p. 111). The "knowing how" type of knowledge is associated with tacit knowledge, and it is thus costly and difficult to transfer between humans.[33]

Two additional concepts are identified as important in relation to knowledge. The first, "absorptive capacity", refers to the ability of actors to add new knowledge to their existing (Cohen and Levinthal, 1990). This ability depends on the previous experience of the actors and is, thus, made up by both explicit and tacit knowledge that have accumulated over time. The second concept, "appropriability" of knowledge, refers to the actor's ability to do something useful and economically valuable with knowledge they acquire over time (Teece, 1986).

These concepts are important since increasing the number of actors with an "expert level" of knowledge is seen as a key issue for any emerging TIS. In this study, it translates to increasing the number of actors that are able to appropriate on acquired knowledge necessary for building and diffusing commercial-scale biomass gasification plants for the production of second-generation fuels and other chemicals.

Achieving this expert level of knowledge involves acquiring primarily the know-how type of knowledge (Dreyfus et al., 1986; Grant, 1996). Dreyfus et al. (1986) and Flyvbjerg (2001) emphasise that the core of human learning and achieving an expert level of knowledge lies in gaining real-life experience (learning by doing)—regardless if the learning process involves

[33] One could also add *knowing what, knowing why, knowing who, knowing when,* and *knowing where* (Lundvall and Johnson, 1994). However, these types of knowledge are also explicit in nature and is here categorised as *knowing about.*

playing chess, performing brain surgery, constructing wind power mills, or gasification plants for the production of second-generation fuels.

In terms the function's impact on structural build-up it obviously strengthens the structural element technology. Previous literature has also emphasised that knowledge is developed and diffused through networks and that these networks are also likely to be strengthened by a strong function of *knowledge development and diffusion* (Carlsson and Stankiewicz, 1991; Lundvall, 1992; Bergek et al., 2008b).

In terms of the function's relationships to other functions, the development of new knowledge may serve as a basis for strengthening *entrepreneurial experimentation* and *materialisation,* since new scientific discoveries may enable new types of experiments or the construction of new research infrastructures. It may also strengthen *legitimation* and *influence on the direction of search,* as new knowledge may prove the new technology more beneficial in some desirable and previously unknown aspects.

2.3.2 Influence on the direction of search

The function of *influence on the direction of search*[34] refers to the process of strengthening the incentives and/or pressures for organisations to enter the technological field. These may come in the form of possible entrepreneurial or political visions, as well as investors' and others expectations of growth potential. Such expectation may rise from personal beliefs but also from experiences and observation of growth in related TIS, or the same TIS in other countries (Bergek et al., 2008b). In a very early phase, the function includes how system builders manage to define the technological opportunity and make it attractive for other actors to enter and further develop the TIS (Hellsmark and Jacobsson, 2009).

It also incorporates regulations and policies that create new opportunities and stimulate innovation (Porter, 1990b; Porter and Van der Linde, 1995), the articulation of demand from leading customers and their involvement in innovation processes (Von Hippel, 1986), as well as reverse salients that actors are forced to address (Hughes, 1983).

[34] The shorter *direction of search* is commonly used throughout the text to replace *influence on the direction of search.*

In addition, crises or other factors exogenous to the TIS may be an important impetus for redirecting established search processes. Such crises can, for example, result from declining rates of return in certain firms or sectors, or general changes on a "landscape" level (Geels and Schot, 2007). Examples of such exogenous changes on a landscape level are the emergence of an oil crisis or other acute shortage of resources, the climate change debate, wars, and so on.

In terms of the function's relationships to other functions and its impact on structural build-up, *direction of search* and the function of *legitimation* are strongly related to one another. Strengthening these functions is important for attracting new entrants into a field. For instance, an exogenous event on a landscape level—such as an oil crisis—may strengthen the function of *legitimation* of a certain TIS, which in turn may influence the *direction of search* for new opportunities by actors in other industries. Hence, when these two functions are strengthened, the structural element of actors is likely to be strengthened.

2.3.3 Legitimation

The function of *legitimation* refers to the process of strengthening social acceptance and compliance with relevant institutions (Bergek et al., 2008b).

Legitimacy is viewed as a key strategic resource for firms in a given TIS, since it can be used to mobilise additional strategic resources (Suchman, 1995; Zimmerman and Zeitz, 2002). Furthermore, it is a prerequisite for new actors to enter the TIS, which brings resources and legitimacy to the field. Legitimacy can be both granted to a given TIS by exogenous factors to the system, or created through intentional activities by the actors (Hellsmark and Jacobsson, 2009).

For example, the climate change debate has increased the legitimacy of the use of biomass as compared to coal, and the number of actors interested in pursuing opportunities with biomass as a feed-stock is increasing. Moreover, with the increased legitimacy of biomass, general schemes of funding have been made available for researchers and entrepreneurs interested in the field.

Nevertheless, a new field is seldom granted legitimacy from the start, and new industries have to overcome their “liability of newness” (Zimmerman and Zeitz, 2002). In the early stages of a formative phase, legitimation mainly involves getting the technology accepted as a desirable and viable alternative to incumbent substitutes. It involves achieving favourable expert assessments in terms of system studies, cost-benefits analyses and various rational arguments. These actions are part of “the politics of shaping expectations and of defining desirability” (Bergek et al., 2008c, p. 581).

In a later stage, when various knowledge networks have been formed and there is a base for creating “advocacy coalitions” between different actors, the “liability of newness” can be overcome (Van de Ven, 2005). The work of an advocacy coalition can involve attempts to align the institutional framework either through complying with or manipulating the existing, or the creation of new rules that support the development of the TIS.

In terms of the function’s relationships to other functions and its impact on structural build-up, *legitimation* and *direction of search* have already been argued to be strongly related and that they strengthen the actor structure. In addition, they are also identified as key processes for strengthening the structural element of institutions.

2.3.4 Resource mobilisation

The function of *resource mobilisation* refers to the process of strengthening the extent to which actors within the TIS are able to mobilise various types of resources, including technical experts, engineers, and other human resources. Human resources can be accessed through the educational system and from competing TISs or related sectoral systems of innovation. They can also be accessed through special research and development programmes that enhance the level of knowledge for people in a given field. Other types of resources include financial capital (from venture financiers, government, diversifying firms, etc.), complementary products, services, and network infrastructure (Bergek et al., 2008b; Bergek et al., 2008c).

In terms of the function’s impact on structural build-up and its relationships to other functions, when *resource mobilisation* is strengthened the resources can be used as a basic input for all activities in the system. Thus, strengthening resource mobilisation enables further development and can potentially strengthen all of the structural elements and functions of the TIS.

2.3.5 Entrepreneurial experimentation

The function of *entrepreneurial experimentation* refers to the process of testing new technologies, applications and markets, whereby new opportunities are created and a learning process is unfolded (Bergek et al., 2008b; Bergek et al., 2008c).

By conducting various types, as well as many entrepreneurial experiments, the uncertainties surrounding a new TIS are reduced, as is the risk of failure for the TIS as a whole[35] (Bergek et al., 2008b; Jacobsson, 2008). The strength of this process is highly dependent on the entry of many actors who undertake these experiments. A strong function would build (applied) knowledge and reduce uncertainties (e.g. market and technological) that may pave the way for new entrants.

In terms of the function's relationships to other functions and its impact on structural build-up, it is strongly related to the functions of *materialisation, knowledge development and diffusion,* and ultimately strengthens the structural elements of technology and actors. In turn, *entrepreneurial experimentation* is enabled by a strong *materialisation* and *knowledge development*, since it provides a technology base upon which additional experiments can be conducted.

2.3.6 Materialisation

The function of *materialisation* refers to the process of strengthening the development and investment in artefacts such as products, production plants and physical infrastructure (Bergek et al., 2008c).

In the early phase of a TIS, the technological elements may be severely underdeveloped. There may be a lack of instruments and other types of laboratory equipment that must be

[35] The risk of failure for an individual actor may still remain high.

invented (Fogelberg and Sandén, 2008). In addition, there may be a lack of intermediate products, and physical infrastructure that must be developed or invested in.

Demonstration projects are a particular type of *materialisation* that is important in the industrialisation of new knowledge fields (Karlström and Sandén, 2004). They play an important role for the formation of knowledge networks, reducing technical uncertainties, and facilitating learning that can be used to support decisions on technology choice. However, they may also raise public awareness of the technology, strengthen its legitimacy and expose system weaknesses such as various institutional barriers. Since a variety of actors with a common interest come together in demonstration projects, they can form a potential base for creating advocacy coalitions that can address these barriers (Karlström and Sandén, 2004).

In terms of the function's impact on structural build-up, strengthening materialisation is key for strengthening the structural element of technology (Bergek et al., 2008c) and may be conducive to the formation of both knowledge and political networks. In terms of the function's relationships to other functions, *materialisation* is, as argued above, strongly related to the functions of *knowledge development and entrepreneurial experimentation*, but can also impact on *legitimation* and *direction of search*.

2.3.7 Market formation

The function of *market formation* refers to the process of strengthening the factors driving the diffusion of the technology (Bergek et al., 2008b; Bergek et al., 2008c).

For an emerging TIS, markets may not exist or be greatly underdeveloped, as the technology suffers from a poor price/performance ratio and uncertainties exist in many dimensions. These uncertainties are reduced and the price/performance ratio is improved when the function is strengthened through, for example, the articulation of demand from customers, institutional change and the realisation of economies of scale.

It is also through this process, as well as the processes of *entrepreneurial experimentation* and *materialisation,* that society as a whole can learn about a new TIS and react to its development. Furthermore, the advocates of a new TIS learn about its role in society and act/react upon the reactions from actors external to the TIS.

The process of market formation often runs through various stages such as "nursing" or "niche markets" (Erickson and Maitland, 1989; Kemp et al., 1998), possibly in the form of demonstration projects, bridging markets (Andersson and Jacobsson, 2000) and, eventually, mass markets.

In terms of the function's impact on structural build-up and its relationships to other functions, when *market formation* is strengthened resources are generated and these can be used as basic input to all activities in the system. Thus, market formation enables further development and can potentially strengthen all of the structural elements and functions of the TIS.

2.3.8 Development of positive externalities

The function of *development of positive externalities* refers to the process of strengthening the collective dimension of the innovation and diffusion process—such as how investments by one firm may benefit other firms "free of charge". It also indicates the dynamics of the system, since externalities magnify the impact of the other functions (Bergek et al., 2008b; Bergek et al., 2008c). One can differentiate between externalities, which are primarily geographically bounded, and those available throughout a global TIS, i.e. across national boundaries.

Positive externalities develop based on the common locality and clusters of industries within a nation or smaller geographically defined area were first elaborated on by Marshall (1962 [1890]) and later by Porter (1990a). Three such sources of external economies, in line with Marshall, were specified by Bergek et al. (2008b, p. 418):

- "Emergence of pooled labor markets, which strengthen the 'knowledge development and diffusion' function, in that subsequent entrants can access the knowledge of early entrants by recruiting their staff (and viceversa as time goes by)."
- "Emergence of specialized intermediate goods and service providers; as a division of labor unfolds, costs are reduced and further 'knowledge development and diffusion' is stimulated by specialization and accumulated experience."

- "Information flows and knowledge spill-overs, contributing to the dynamics of 'knowledge development and diffusion'."

When defining an innovation system in terms of its "knowledge and competence flows", it has been argued that these flows " ... may or may not coincide with national borders" (Carlsson and Stankiewicz, 1991, p.93). The external economies may then benefit firms throughout a "global" TIS. For example, when the functions *legitimation* and *direction of search* are strengthened, they may benefit all actors within the "global" TIS.

Similarly, with a strong *materialisation* a new research infrastructure may become available for many actors throughout the global TIS. Based on the new infrastructure, new experiments can be conducted, and results from these experiments can also be shared with actors not directly involved in strengthening the function of *materialisation* in the first place. With a strengthened *market formation,* firms throughout the TIS may compete over the new contracts, even if some firms are favoured over others due to well-established networks or firm-specific industrial policies.

The development of such positive externalities benefits late entrants, which eventually can catch up with the early entrants at a considerably lower cost, for example, by learning from the former's mistakes and developing improved designs. In the end, such externalities may result in the fact that early entrants are out-competed by those who have entered at a later stage (cf. Olleros (1986), Lieberman and Montgomery (1988)).

In terms of the function's impact on structural build-up and its relationships to other functions, the *development of positive externalities* can potentially strengthen all the functions and structural elements of the TIS.

2.3.9 The inter-relationships of the eight functions

As previously mentioned, several of the functions are closely related to each other. One action or event, which strengthens one function, may therefore strengthen others, both directly and indirectly.

Here, an epistemological distinction between three sets of functions is made, as they are associated with the acquisition of the two different types of knowledges—"know how" and "know about"—and where a third set of functions enables the acquisition of such knowledge (see Table 2.3).

Table 2.3: An epistemological distinction between three sets of functions.

Set 1: acquisition of "know how"	*Knowledge development and diffusion, entrepreneurial experimentation* and *materialisation.*
Set 2: acquisition of "know about"	*Direction of search* and *legitimation.*
Set 3: enables the acquisition of knowledge	*Resource mobilisation, market formation* and *development of positive externalities.*

The first set of functions includes *knowledge development and diffusion*, *entrepreneurial experimentation* and *materialisation*. As previously mentioned, strengthening *knowledge development and diffusion* has often been placed at the heart of the innovation process (cf. Bergek et al. (2008b)). Strengthening the function is essential for the industrialisation of a new knowledge field, and it was previously argued that the actors would need to develop an expert level of "knowing how" in terms of, for example, building new types of plants.

Acquiring that level and type of knowledge goes beyond conducting basic and applied research, associated primarily with the function of *knowledge development and diffusion*. Strengthening the level of "know how" involves acquiring real semi-commercial and commercial experience with the technology and must, therefore, include a process in which the functions of *entrepreneurial experimentation* and *materialisation* are also strengthened. Thus, it is only by strengthening all these three functions that the actors can fully benefit from "learning by doing" and with time acquire the primarily tacit skills necessary to construct competitive, commercial-scale biomass gasification plants, or other types of new equipments.

The second set of functions, *direction of search* and *legitimation*, is primarily associated with "knowing about" the TIS. The successful construction of demonstration plants may strengthen these functions, as the technology becomes well-known. In addition, the system builders can undertake actions to consciously and strategically strengthen the functions by publishing reports and statements, gain positive media attention, or by other means influence public perception—or the perception of certain stakeholders—of the field. This set of functions can also be strengthened by exogenous events occurring on a landscape level such as a debate on climate change, beyond the control of individual actors. Strengthening the “know about” functions of the TIS is crucial for the actors’ ability to form alliances or political networks with the objective of aligning the institutional framework to the TIS.

The third set*, resource mobilisation, market formation* and *the development of positive externalities* are basic inputs to all activities in the system and works as a catalyst as the system matures. Without strengthening the three functions, the actors will not have the means to strengthen the above-mentioned “know how” or “know about” sets of functions. They are, thus, seen as the enablers in the system. The complete system dynamics of the TIS will now be outlined.

2.4 Functional and structural dynamics

Having explained the structural elements and functions of a TIS, as well as some of their interrelationships, the complete dynamics of a TIS can now be summarised by five main relationships (see Figure 2.2): (1) the dynamics between structural entities; (2) the influence of the structural entities on the functions; (3) the influence of exogenous factors on the functions; (4) the internal dynamics of the functions; and (5) the feedback from the functions to the structure.

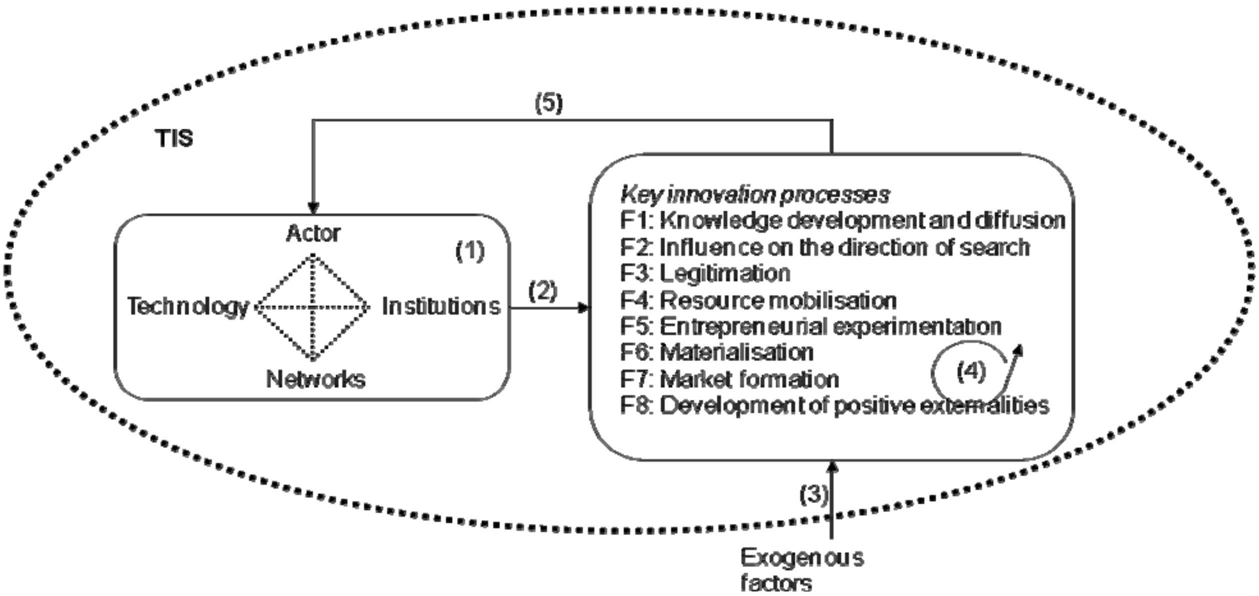

Figure 2.2: A schematic representation of the dynamics of a technological innovation system.

In Section 2.2, I briefly dealt with the dynamics between structural elements (1). The internal dynamics of the functions (4), and how the strengthening of the functions may feed-back and result in a structural build-up (5) were briefly discussed with respect to each of the eight functions in Section 2.3. The complete dynamics of a TIS will now be further described and analysed.

To begin with, the characteristics of the structure impact on the strength of the functions (2). An example of a structural change that may strengthen the key innovation and diffusion processes is the entry of new firms. These bring various types of resources into the TIS that may strengthen not only *resource mobilisation* but also the processes of *knowledge development and diffusion* (as resources may be devoted to research and development), and *legitimation* (if the firm either has a good name and/or devotes resources to promote the legitimacy of the new technology). Of course, as and when new firms test new design concepts, build plants and infrastructure, the processes of *entrepreneurial experimentation* and *materialisation* are strengthened. However, the strength of the functions cannot be fully explained by the characteristics and impact of the TIS elements (1, 2).

As emphasised in the original work on "functions of innovation systems", the strength of the functions are also determined by factors found at other system levels (Johnson and

Jacobsson, 2001, p. 93): “In the context of an emerging technological system, these factors may be fully technology specific, but may also influence several technological systems simultaneously. Hence, they can be derived from a system perspective using different units of analysis: technology, industry, nation.”

Hence, the driving forces behind system development are both endogenous and exogenous[36] (see (3) in Figure 2.2). Examples of exogenous factors[37] are accidents like that in Chernobyl, the climate change debate, and EU-wide legislation on air quality (see *influence of direction of search* in Section 2.3.2). Such changes may inflict pressure on the dominant TIS (Raven, 2005) and open up opportunities for a TIS with regard to *market formation*. They may also strengthen other functions, particularly *legitimation* and the *influence on the direction of search* and, thereby, if and how actors perceive opportunities in the new TIS.[38]

As the functions are strengthened by endogenous (2) or exogenous (3) factors, they may feedback and further strengthen various elements of the structure (5). For instance, strengthened *legitimation* and *influence on the direction of search* would be expected to motivate even more actors to enter the TIS. Indirectly, this may affect the formation of networks. Strengthened *legitimation* may also induce an institutional alignment. With a stronger *resource mobilisation*, further *materialisation* of the technology may take place, which builds up the structural element of technology.

[36] This means determining factors, found at the levels of “regimes” and “landscape” in Strategic Niche Management (see, Geels and Schot (2007) for a typology), are incorporated.

[37] A distinction between endogenous and exogenous factors begs the question of how the borders of the system in focus are set. In the original work on “functions of innovation systems”, the setting of borders was not a main concern simply because the focus was not primarily on the impact of the functions on structural dynamics. With a TIS framework, it is the knowledge base that is the starting point for defining the system in focus (i.e., the structural element “Technology”). This knowledge base is dynamic and the system borders are fluid. As the knowledge base (design space) is altered by, for example, the inclusion of a new element of knowledge, new actors may be incorporated into the system, new networks may be formed, and the range of relevant institutions may expand. In a formative phase, it is therefore argued that seeking to define strict borders of the TIS is a less meaningful exercise, and it is preferred to speak in terms of the focus on the analysis (Carlsson et al., 2002a; Carlsson et al., 2002b). Yet, the importance of defining the focus is acknowledged, and in this particular case the focus is on the structural elements that contribute to the development and diffusion of the technology of biomass gasification. Some of these may, of course, be shared with other TISs, which means that there may be important interactions with those TISs—challenging the usefulness of a narrow system delineation (Bergek et al., 2008b). For a useful discussion on system delineation, see also Markard and Truffer (2008).

[38] Exogenous factors may also reduce the strength of the functions. For instance, the development of a competing TIS may reduce market formation and entrepreneurial experiments simply by drawing the attention of main actors to another TIS.

The internal dynamics of the functions are another source of dynamics (4) that now can be further explained. Their interaction goes through elements of the structure, which either can be endogenous (5) or exogenous to the system (3). For analytical purposes, one can "shortcut" (5) and (2) and only focus on the internal dynamics of the functions.[39] In a best-case scenario, the inter-relatedness of the functions may cause a spiral of positive events. For example, with strengthened *legitimation*, *resource mobilisation* is simplified and more *entrepreneurial experiments* can be made. This may involve building a new plant (*materialisation*), which if run successfully may have a strong signalling effect, further increasing *legitimation* of the technology (complete loop). Hekkert et al. (2007) label such interactions as "motors" in the dynamics of a TIS and Suurs (2009) have identified various types of such motors.

To summarise, a series of endogenous and exogenous events may strengthen the key innovation processes. Due to the functional inter-relationships, a positive development in one or several functions may spill over to and strengthen the others. A strengthened set of functions feeds back to the structural entities of the TIS. These positive feedback loops between structure to functions and back to structure may give rise to "virtuous cycles".[40] When these self-reinforcing processes become strong enough, the development of the system no longer stands or falls on the positive or negative activities undertaken by a single or few actors inside or outside the system. It is at this point that the system can reach a "momentum of its own" (Hughes, 1987) and moves into a phase marked by rapid market growth.

However, the opposite situation could also prevail, in which functions are never developed properly or where a weakened structure and functions give rise to vicious circles (Negro, 2007). Therefore, from the perspective of an emerging TIS, it is vital to identify structural and functional system weaknesses, as well as exogenous factors, that obstruct the development of the TIS.[41] For instance, an endogenous structural and functional system weakness may be

[39] How the functions may impact structural elements that are exogenous to the system is not discussed further.
[40] By analogy with a cumulative causation (Myrdal, 1957) or increasing returns (Arthur, 1989). Myrdal (1957) has argued that studying this type of inter-dependency resulting in a cumulative causation is a main scientific task.
[41] See Johnson and Jacobsson, (2000); Unruh (2002); Bergek and Jacobsson (2004).

poorly developed learning and "political" networks that limit *knowledge development and diffusion,* as well as *legitimation*, while an exogenous factor may be a strong bias in the selection environment in favour of incumbent technologies.

Weak functions and strong external factors inhibiting growth of the TIS also result in many uncertainties that may discourage investors and other actors from entering the new TIS. These various types of uncertainties, structural and functional weaknesses, as well as negative exogenous factors—which typically dominate the formative phase of a TIS—will now be explained and further elaborated on. A framework for identifying and addressing these types of weakness will also be developed.

2.5 The role of system builders and policymakers for addressing system weaknesses

It was previously argued that the complete system dynamics of the TIS should be described in both structural and functional terms and that an analysis of the five main relationships, outlined above, should be included in the description. The basis for conducting such an analysis has already been set out.

In this section, the focus is turned to the specific characteristics of the dynamics during the formative phase, as well as the potential of using the approach as a guide for policy intervention. First, the characteristics of a TIS during the formative phase are described in terms of a set of dominant uncertainties, as well as structural and functional system weaknesses. Second, the rationale of using an approach in which the structural and functional system weaknesses are identified and used as guidance for policy intervention will be outlined. Third, the framework for identifying which system weaknesses should be addressed by policymakers is further developed based on the nature of and limits to the system builder(s') capacity of identifying and acting upon such system weaknesses.

2.5.1 Uncertainties and system weaknesses in the formative phase

During the formative phase of a TIS, the system emerges from chaos to a more or less coherent structure (Hughes, 1987). During this time, it is likely to be characterised by various uncertainties, weak and fragmented links between the different weak structural elements and weak functions, resulting in various system weaknesses of the TIS. Such uncertainties and system weaknesses will now be described.

In the previous literature, three dominant uncertainties that influence investors, policymakers and other actors in the formative phase of a TIS have been mentioned: technical, market and institutional (Jacobsson and Bergek, 2004). However, one can also argue for the existence of organisational uncertainties. To begin with, technical uncertainties refer to the evolution of many competing technical designs, often with poor price/performance ratios. A series of “secondary innovation” are normally required for that ratio to improve, and as the market moves into a growth phase, the number of competing designs is reduced (Schmookler, 1966; Abernathy and Utterback, 1978).

Organisational uncertainties are associated with uncertainties during the formation of a supply chain. In the formation of a new TIS, the role of various firms is often unclear and the willingness of new and old firms to perform certain tasks within that supply chain can be uncertain.

Market uncertainties refer to the largely unknown size of the future markets. The size of future markets is largely unknown since it is next to impossible to foresee the possible success of substituting alternatives, future commodity prices, changes in customer preferences or the potential of secondary innovations, opening-up new and unexpected markets. Finally, institutional uncertainties refer to if and how regulatory changes are made to support the new technology, as well as if beliefs and values will be aligned to it.

These uncertainties act, of course, as obstacles to firm entry and severely hinder the development of the system. The development of strong system functions would reduce these uncertainties, but this is often a very long and difficult process that last throughout the formative phase. Consequently, the system runs the risk of remaining weak also in structural terms.

With regard to technology there may be no technological base and infrastructure or it may be severely underdeveloped. Thus, there may be a lack of instruments, demonstration facilities, clean rooms, or other types of science and technology infrastructure for the system to develop (Fogelberg and Sandén, 2008). There may also be few or weak actors with sets of underdeveloped or inadequate resources. The actors may also be too small to take on a large project or have the wrong competence for the task required.

In addition, the institutional rule structure is normally not aligned to the TIS but favours the incumbent technologies. The lack of supporting institutions often serves as one of the main barriers for the development of a new TIS. To achieve such an alignment, it is often required that knowledge and political networks are well developed, i.e. there are several actors working together towards a common goal (Van de Ven, 2005). Such networks and institutional alignments take time to develop and accomplish, and requires that eventual conflicts in the TIS are addressed.

Thus, the structural elements are often very weak in the formative phase of a TIS. Analysing system weakness in structural terms is possible for any given IS. At least since Lundvall (1992), the analysis of such system weaknesses, for various IS, has been used as a tool for policy intervention. Various types of system weaknesses, also referred to as system failures, have been identified in the literature.[42] However, the purpose here is not to provide a review of that literature.[43] Instead, it is rather that such an analysis should be complemented with an analysis of the system weaknesses in functional terms to allow us to explain why the structure is weak and, thereby, improve the possibilities of suggesting appropriate policy measures (see Figure 2.2).

Just like the structure, the functions can at best be expected to be weak during the formative phase. There may be a lack of ongoing activities that can strengthen *knowledge*

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[42] Please view Klein Woolthuis (2005) and Foray (2009) for an overview. In previous literature, reference is often made to "system failure" instead of "system weaknesses", which will be used in this thesis. The reasons for using the concept of system weaknesses instead of system failure will be outlined in the subsequent section.

[43] In a literature overview by Klein Woolthuis et al. (2005), a sum of eight commonly discussed and general structural system "failures" were identified: (1) Infrastructure failures: the lack of physical infrastructure such as IT, roads, and science and technology infrastructure (Smith, 1996; Edquist et al., 1998). (2) Transition failures: the inability of firms to adapt to new technological developments (Smith, 1996). (3) Lock-in/path dependency failures: the inability of complete social systems to adapt to new technological paradigms (Smith, 1996). (4) Hard institutional failures: the failures in the framework of regulations and the general legal system (Smith, 1996). (5) Soft institutional failures: the failures in the social institutions such as political, culture and values (Smith, 1996; Carlsson and Jacobsson, 1997). (6) Strong network failures: the "blindness" that evolves if actors have close links and miss out on new outside developments (Carlsson and Jacobsson, 1997; Christensen, 1997). (7) Weak network failures: the lack of linkages between actors (Carlsson and Jacobsson, 1997). (8) Capabilities failure: the lack of absorptive capacity, specifically in small firms, to learn about new technologies (Cohen and Levinthal, 1990; Malerba, 1996; Smith, 1996).

development and diffusion, *entrepreneurial experimentation and materialisation*. If all these functions are weak, the "knowing how" type of knowledge required may, for example, not develop adequately. In addition, there may be a lack of basic research contributing by explaining certain phenomena and, thereby, strengthening the explicit knowledge base "knowing about". The number of *entrepreneurial experiments* may be too few, which in turn may hamper further knowledge development and the generation of new ideas for the necessary secondary innovations. When the activities strengthening *materialisation* are few, knowledge development that requires the establishment of an infrastructure cannot be made. Markets are often small and underdeveloped, and potential customers are hesitant to take on the role of being first. Such lack of *market formation* hampers the very important and interactive type of learning made possible in the first supplier and customer relations (Von Hippel, 1986; Lundvall and Johnson, 1994).

The remaining functions of *resource mobilisation*, *direction of search*, *legitimation,* and the *development of positive externalities* may also be weak and underdeveloped in the formative phase. There may not be enough financial or human resources for developing the field such as a lack of technology experts. All new technologies have been argued to suffer from a "liability of newness" (Zimmerman and Zeitz, 2002). Therefore, the system may be characterised as weak in terms of its legitimacy (*legitimation*), which may result in, for example, difficulties obtaining necessary environmental and building permits, or other types of resources necessary for developing the field. If the system is weak because of its legitimacy, it is also weak in terms of *direction of search* and few actors can be expected to be attracted to enter the field.[44] A weak function with regard to the *development of positive externalities* is a natural state in the formative phase of a TIS. There is, for example, usually a very limited pooled labour market, lack of specialised equipment manufacturers, and other actors that can transfer experience from one firm to another.

[44] A TIS can, however, be seen as legitimate, but still suffer from a weak direction of search. For example, an oil price or regulatory framework in an ongoing state of flux may weaken the function and, thereby, discourage potential investors.

Hence, large technical, market, organisational, and institutional uncertainties discourage new actors from entering the TIS in its formative phase. This may lead to a continued presence of various system weaknesses in structural and functional terms.

2.5.2 Policy intervention, system weaknesses and system builders

The outcome of attempts aimed at resolving these uncertainties and system weaknesses are in themselves highly unpredictable, and the TIS may have to undergo several intermediate periods, or *episodes*, which are dominated by specific patterns of interaction between actors and the other elements of the structure before they can be resolved (Suurs et al., 2010). The time frame for these episodes cannot be known before-hand, and forming an embryonic TIS is a process that can last for several decades (Carlsson and Jacobsson, 1997; Grubler, 1998; Breshanan et al., 2001; Wilson, 2009).

Extensive arguments have been made that policy interventions based on the identification of system weaknesses[45] provide an encompassing tool for stimulating innovation, the creation of new industries and economic growth, especially when compared with the conventional market failure approach (Lundvall, 1992; Lundvall and Johnson, 1994; Malerba, 1996; Smith, 1996; Carlsson and Jacobsson, 1997; Metcalfe and Georghiou, 1997; Smith, 2000b; Edquist, 2002; Metcalfe, 2004; Smits and Kuhlmann, 2004; Klein Woolthuis et al., 2005; Lundvall, 2007; Foray, 2009; Bergek et al., 2010b).[46]

Yet, there are limits of the usefulness of policy intervention. One should not forget that most functions in modern societies are best fulfilled by the market mechanism and capitalist firms. This is also true in terms of identifying and acting upon system weaknesses, or as “ ... Smits and Kuhlmann (2004) put it: ‘[O]ne should not overestimate the instrumental power of public policy vis-à-vis other actors in complex policy making arenas.’ Individual firms, groups

[45] It has been argued that using the concept of “failure” from a system perspective is misleading, since it is not used with respect to an optimal situation. Instead, it has been proposed that using the concept of “system weaknesses”, as rationale from policy intervention, is more in line with a system perspective (Malerba, 1996).

[46] For the purpose of this thesis, it is of no interest to go into the details concerning the shortcomings with the market failure approach. The main objection, from the above-mentioned authors, has been that it builds on a static (neoclassic) framework on how markets operate. Market failures are identified based on the divergence from what would be considered an optimal path towards perfect competition and equilibrium.

of entrepreneurs, industry association and other interest organization may very well identify and act upon system weaknesses in their own self-interest" (Bergek et al., 2010b, p. 120).[47]

There is, therefore, a need to be able to distinguish between the role of policymakers and the other actors in addressing system weaknesses. There is, of course, no need for policymakers to engage in a costly search processes and target various structural and functional system weaknesses in the emergence of a new TIS if the system builders, and other actors, can identify and address these weaknesses themselves. However, for identifying which system weaknesses that can be addressed by system builders and which have to be addressed by policymakers, an improved conceptualisation of the system building role is called for.

Previously, it has been emphasised that exogenous factors to the TIS dominate in the early phase of system formation simply because the structural components are weak and the actors' ability to strengthen the key innovation and diffusion processes are necessarily limited (Raven, 2005; Bergek et al., 2008a).

The role of the actor in the formative phase has therefore been downplayed in the empirical analyses, even though opportunities for system building activities by early entrants into a TIS have been identified. In the literature, the prime mover has been given an key role in the formation of a new TIS (Carlsson and Jacobsson, 1997). The prime mover acts on a perceived opportunity, fulfilling several important tasks in the evolution of the new system such as: " … raise awareness, undertake investment in the new technology, give it legitimacy and diffuse it through various mechanisms to other actors" (Carlsson and Jacobsson, 1997, p. 305).

The view on the actor in previous TIS studies is inherited from evolutionary theory, where the " … firms are the key actor, not the individual human beings ... individuals are viewed as interchangeable and their actions determined by the firms they are in" (Nelson, 1995b, p. 68). When reference is made to the prime mover, it is consequently a firm that is in focus (Jacobsson and Bergek, 2004, p. 1498; Jacobsson, 2008, p. 817). On some occasions, it is not a single firm but rather constellations of actors, networks or alliances that collectively act as

[47] Cf. Van de Ven (1993).

prime movers, engaging in system building activities by addressing the various system weaknesses and uncertainties (Jacobsson and Johnson, 2000, p. 637). However, systematic analyses for identifying the range of system builders and their ability to strengthen the key innovation and diffusion processes have previously not been undertaken.

The system builder is here defined as an individual actor, an alliance or a network of actors building and strengthening the structure, as well as several of the functions (if not all) in an emerging TIS. The system builder reduces the various types of uncertainties and addresses system weaknesses in a given TIS.

Although the system builder can include an alliance of actors, it will not include all of the actors within the TIS. There will, most likely, be competing system builders working on alternative trajectories and projects within the TIS that can be in stark conflict with each other, requiring different types of institutional and organisational set-ups.

An analysis of the system builder departs from the individual actor(s) and conceptualises these as being embedded in a general structure[48] (cf. Giddens (1984a)). This structure both constrains and enables the system builder(s) to address system weaknesses, to reduce further uncertainties and to strengthen the TIS.

Hughes (1987, p. 52) argues that such system builders possess a capacity " … to construct or force unity from diversity, centralization in the face of pluralism, and coherence from chaos." Such an agent may build artefacts but does not concern himself/herself with artefacts alone, but must also consider the way in which these relate to social, economic, political, and scientific factors (Law, 1987a, p. 112).

Hellsmark and Jacobsson (2009) conceptualise such an actor as an individual equipped with a "transformative capacity". When this agent acts, he or she intervenes in the world and makes a difference to a pre-existing state of affairs or course of events. (Giddens, 1984a, p. 14-15).[49] It is proposed that the transformative capacity can be analysed by the ability of the

[48] From a system perspective, the general structure is made up of the various structural elements on NSI, RSI and SSI levels of analysis (see section 2.1).

[49] The content and limits of the transformative capacity can partly be explained by the ability of the agent to control and mobilise resources. Giddenns (1984a, p. 15) defines resources as " ... structured properties of social

system builder(s) to strengthen the eight key processes (functions of a TIS) by building structure or by undertaking other types of activities, which strengthen the functions directly.

The transformative capacity can thus be analysed by the actors' ability to collude and create alliances with other actors[50], creating networks, creating new firms and technology, and thereby strengthen the structural elements of the TIS directly. In addition, it can be analysed by the actors' ability to strengthen the various function as they undertake a wide range of activities. For example, an academic who is a member of an advisory group to the government may speak in favour of a technology or he/she may point to risks associated with the very same technology. Similarly, a CEO may decide to diversify and invest in a new technology such as thin film solar cells. These activities are linked to the micro-level of discrete actors (Markard and Truffer, 2008) and contribute to the formation and strengthening of particular functions (in these cases *legitimation* and *entrepreneurial experimentation*).[51]

Hence, it is not sufficient to focus on the system builder's impact on the structural elements alone. Focus must instead be on what the system builders accomplish in terms of strengthening the key processes of innovation and diffusion, either directly or through forming structural elements. The transformative capacity, thus, involves the collective or individual ability to:

a) create and diffuse new knowledge, access and combine new and conventional knowledge from different fields.
b) influence the direction of search of would-be entrants, including defining opportunities within the field and making it attractive for new entrants.
c) create legitimacy for the new technology and/or products.
d) attract and form human and financial resources, as well as complementary assets.
e) undertake entrepreneurial experimentations by testing new concepts, product designs and business models.

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systems … ". This broad and general definition is, however, not particularly helpful when we would like to explain the content and limits of the transformative capacity of a system builder.

[50] These alliances may include not only other firms but also universities, institutes, governmental agencies, lobby organisations, and other policymakers.

[51] See Markard and Truffer (2008) for a useful discussion on the differences between "activities" and "functions".

f) develop and invest in artefacts such as products, production plants and physical infrastructure.
g) define and form first markets for the technology and/or products.
h) act as a channel or create means by which positive external economies are generated, strengthening the impact of the other functions.

Barbalet (1985) points out that it is not possible to understand the extent of the transformative capacity of an individual if the "intentional" and "frictional" resistance, which such an agent will encounter, is not taken into account. The intentional resistance is here interpreted as those obstacles that come out of deliberate actions by actors with opposing interests—in other words exogenous mechanisms that obstruct the formation of strong functions. Frictional resistance is interpreted as problems that are non-intentional in nature and these may be both endogenous to the system such as inadequate networks,[52] but also exogenous such as built-in biases towards incumbent technologies into existing institutions (see e.g. Carlsson and Jacobsson (1997) and Unruh (2000)). Therefore, both types of resistance constitute mechanisms that increase uncertainties and weaken the system in both structural and functional terms, thereby obstructing the formation of a new TIS (Bergek and Jacobsson, 2003).

In this thesis, the role of actors as system builder(s) is re-examined with an increased focus on the limits of the system builder(s') abilities to influence the formation of a new TIS. It has been argued that the strength of the frictional and intentional resistance will limit the transformative capacity of the system builder. If the system builders can be identified and their transformative capacity analysed, it is possible to identify which system weaknesses and uncertainties the system builders can be expected to resolve by themselves and which system weaknesses and uncertainties need to be resolved through policy intervention on different levels. With this contribution to the TIS framework, the conceptualisation of the individual actor as a system builder and their ability to act upon various system weaknesses in a TIS (i.e. transformative capacity) is thereby improved. The conceptualisation paves the way for assessing what is possible to achieve within a certain time frame, given the current policy regimes and abilities of the actors. Furthermore, it helps to identify policy

[52] Another type of frictional resistance may be a lack of interest by incumbents in the new technology.

interventions that may be necessary to reach various higher level goals associated with the development of a given TIS.

2.6 Research Questions

The overall purpose of this thesis was stated in the introduction as to:

" ...analyse the role of the system builders in the emergence of an industry with the capacity to realise the potential of gasified biomass for the production of second-generation transportation fuels and other chemicals within the European Union."

In this chapter, it has been argued that an improved conceptualisation of the system building role would provide a useful tool for policymakers in identifying system weaknesses that would require policy interventions for supporting TISs of strategic importance.

For addressing the aforementioned purpose, it has been broken down into four research questions. The questions address the limits of the system builders' transformative capacity as a means of identifying a set of system weaknesses on a national and an EU level. By elaborating on these weaknesses, the goal is to identify areas that require policy intervention in order for the TIS of biomass gasification to progress.

However, the first question takes a step back and is more of an empirical one—addressing the somewhat ambiguous literature in which Schumpeter (1934) and Hughes (1983; 1987) emphasise the role of the individual in an emerging TIS, while others assign the system building role primarily to firms or networks of firms (Jacobsson and Johnson, 2000; Jacobsson and Bergek, 2004). Hence, the first question is formulated as:

1) *Who act as system builders in the different national contexts?*

After establishing what type of actors take on the role of system builders in the case of biomass gasification and in the four different case study countries, the focus is turned to analysing the nature and extent of their transformative capacity. It was previously emphasised that actors are not only constrained but are also enabled by the structure in which they are embedded (Giddens, 1984a; Scott, 2008). It is central to further analyse *how* and to what *extent* these actors make use of the general structure to form or strengthen the structure and the various functions of the TIS. Hence, the second research question is formulated as:

2) *What characterises the nature and extent of the system builders' transformative capacity?*

    a) *How do the system builders make use of the general structure in which they are embedded to form or strengthen the structure and the various functions of the TIS?*

    b) *To which extent do the system builders manage to strengthen the structure and functions of the TIS?*

The third and fourth questions focus on explaining the eventual limits of the system builders' transformative capacity. These limits are then used for the identification of system weaknesses that remain to be resolved by the system builders themselves, or through policy intervention in the various countries and on an EU level. Research questions three and four are formulated as:

3) *What are the limits to the system builders' transformative capacity and how can these limits be explained?*

4) *Given these limits, which system weaknesses remain to be resolved by system builders and policymakers on different levels (national and EU)?*

These research questions are analysed and answered for each case study country in Part II of this thesis (see Chapters V-VIII). A cross-country analysis is undertaken in Chapter IX (Part III of the thesis). On the basis of this analysis, the main remaining system weaknesses and uncertainties at the EU-level are specified, along with the main policy options for addressing these (see Chapter XI). Further implications for policymakers and system builders are specified in Chapter XII.

Chapter III
Dynamics of the design space, applications and markets

"Many aspects of technological changes, in order to be adequately understood, must be examined in terms of particular historical sequences, for in technological change as in other aspects of human ingenuity, one thing often leads to another – not in a strictly deterministic sense, but in the more modest sense that doing something successfully creates a capacity for doing other things." (Rosenberg, 1976, p. 30)

Gasification is, in the broadest sense, the thermal conversion of any carbon-based fuel to a gaseous product with a usable heating value. It includes pyrolysis, in which the carbon conversion is incomplete and occurs in the absence of oxygen. It also includes partial oxidation, in which an oxidant (gasification agent) reacts with a carbon-based fuel and where the oxidant may be a combination of air or oxygen and steam. Both processes result in a gas with a usable heating value, consisting of various proportions of carbon monoxide, methane and hydrogen (Higman and van der Burgt, 2003).

The reaction temperature is of great importance to gasification. The lower the temperature, the less carbon is converted into a usable gas—leaving more residues in the gas. These residues are generally less desirable by-products consisting of CO_2, H_2O, C_xH_y aliphatic hydrocarbons, benzene, toluene and tars (Boerrigter et al., 2005).[53] When the reaction temperature is higher, and in the presence of oxygen and steam, more of the carbon is converted and the gas contains less undesirable by-products. At temperatures above 1,000 degrees, all the tars and hydrocarbons are destroyed and the raw gas consists mainly of carbon monoxide and hydrogen. At such high temperatures, however, more heat is produced and the total efficiency of the process may therefore be reduced. The treated version of the raw gas from high temperature gasification is usually referred to as a *synthesis* gas or *syngas*, since it can be used to synthesise (produce) a range of chemical products. The cleaned version of the raw gas originating from low temperature gasification is referred to as

[53] When the gas is used for electricity production, the hydrocarbons also have fuel value (Higman, 2010).

a *product gas*. The amount of cleaning required depends on the application for which the product gas is intended.

The design space of gasification has undergone constant evolution since it was first experimented with during the mid-seventeenth century, resulting in various applications and using many different types of carbon-based feed-stocks. In particular, the technology progressed extensively during the early phase of the industrial revolution in England and during the development of the modern chemical industry in the 1920s to 1940s. In addition, rapid technological development occurred during periods of war and crises. For example during the Second World War, initiatives such as Germany's synthetic fuel programme and the development of a mobile gasification system, in for example Sweden, contributed to extending the design space and allowing for the commercialisation of new applications (based on gasification). Other periods of rapid technological development occurred during the South African trade embargo in order to develop synthetic diesel and during the oil crises when coal and biomass-based gasification systems replaced oil in lime kilns.

Worldwide, the gasification of fossil fuels has played an important role for the production of nitrogenous fertilisers and methanol in the chemical industry since the 1920s with the innovation of the Winkler gasifier, for the production of synthetic diesel since the 1970s, and for power production through the Integrated Gasification Combined Cycle (IGCC) since the 1990s. In the past, the choice of feed-stock has mainly been petroleum and coal, but this is changing rapidly in favour of coal, as well as natural gas if the extremely large gas-to-liquids plant currently under construction in Qatar is included in the statistics (GASIF, 2007).

Since the start of the first oil crisis in 1973, biomass gasification has experienced periods of great interest for the production of chemicals, transportation fuels, electricity and heat. With the current threat of climate change, biomass gasification is once again atop many actors' agenda. The expectation from different advocates of the technology is that gasification will provide a secure supply of relatively modest cost and resource-efficient renewable fuels, heat and electricity. For these expectations to be fulfilled, the design space of gasification must once again be extended to include biomass as a resource for these more advanced applications. Thus, the fundamental question is:

have the past 200 years of fossil fuel gasification, and the recent decades of experiments with biomass as a feed-stock for less advanced applications, created the industrial capacity necessary for commercialising the production of second-generation fuels based on biomass gasification?

Answering that question will take the remainder of this thesis. To start with, however, this chapter will address the historical evolution of the design space, the current technical challenges of biomass gasification, the main strategic alliances and projects in Europe, various applications, and the rationale for realising a market for second-generation fuels. The chapter is divided into four sections. The first section briefly unfolds the historical evolution of the design space of gasification between 1665 and 1950. It also includes an illustration of the case of Sweden and the use of producer gas as an emergency fuel leading up to and during the Second World War. The second section will describe the evolution, structure and current trends of the commercial gasification market. Section three describes the main trajectories for biomass gasification and the technical challenges for constructing commercial systems. The fourth section outlines and analyses the main strategic alliances in realising biomass gasification for advanced applications, as well as the rationale and the risks associated with developing a future market.

3.1 The evolution of a design space

The most recent rediscovery[54] of the gasification process has been associated with Reverend John Clayton and his announcement that he discovered the "spirit of coal" in 1688 (Hutchison, 1985, p. 245). What he had discovered was how to produce a combustible gas from coal through pyrolysis. The discovery was not commercialised, however, and disappeared until well over one hundred years later.

It was then two inventors who initiated the process towards the commercialisation of coal gas—almost at the same time and completely unaware of each other's efforts.[55] In 1792, William Murdoch experimented with the technology in his house and garden in Redruth, England. He " … designed to demonstrate how a viable plant could be constructed and

[54] The use of pyrolysis gas had previously been known in ancient China.

[55] Other experiments with coal gas were conducted before Murdoch and Lebon but were never displayed or received attention (Falkus 1982).

operated to make, store and use coal as an illuminant" (Hutchison, 1985, p. 248-249). However, it was not until he heard about the other inventor's (Phillip Lebon) experiments in Paris that he made serious attempts to commercialise the design. Philippe Lebon experimented with gas lighting and heating, and held the first public display of the new technology in Paris in October 1801. The display received much attention but did not result in a business for Lebon. Before he could continue with his new found invention he enlisted in the French army and was killed in 1804 (Falkus, 1982).

Murdoch, on the other hand, was an engineer employed by the company Boulton & Watt. It was in their machine factory that the first version of the coal gas-based lighting system was installed in 1802. The owners of the company strongly believed in the technology and decided to bring the system to market. Their first customer, George August Lee, was partner in the firm Phillips & Lee, and played a key role in making the system commercially ready. Most importantly, he was willing to take great financial risks in developing the lighting system and implementing it on a full commercial-scale at Phillips & Lee's cotton mill in Manchester. This commitment allowed several teething problems to be overcome and the new technical system to mature. Mr. Lee also suggested several improvements to the design, welcomed visitors—including many other factory owners—to witness the technology and contributed to calculating the cost of the system compared to that of using candles (Falkus, 1982).

The technical system behind gas lighting consisted of several inter-related components, each of which needed to work properly before the system could be commercialised. At the heart of the system was an airtight furnace, which was heated from the outside by burning coal, while the coal inside was thermally decomposed. The high calorific gas appeared as a by-product, since 70 percent of the coal remained in form of coke (Knoef, 2005).

This was far from an environmentally friendly process of gas production. Tars appeared in the combustible gas as a by-product of the manufacturing. These tars were made up of 500 to 3,000 different compounds that are toxic to humans and animal life (Hatheway, 2007). During production these tars were leaked, spilled or discarded into the environment and since they are not susceptible to natural degradation they did not simply disappear. Indeed, the waste from old gas plants continues to present a problem in some areas even today (Hatheway, 2007).

The technology experienced a commercial breakthrough and, with the foundation of London Gas, Light and Coke Company in 1812, moved into a phase characterised by rapid market growth (Higman and van der Burgt, 2003). Consequently, from 1812 onwards the use of combustible gas grew rapidly. By 1850, all major towns with more than 10,000 residents on the US east coast had their own gas works (Hatheway, 2007) as did most towns with as few as 3,000 inhabitants in the UK (Falkus, 1982). Hatheway (2007) estimates that there were approximately 52,000 gas plants in the US alone at the time.

It was not until after the mid-nineteenth century that other applications for the gas were developed such as heat, cooking and power (Falkus, 1982). The gas was initially so expensive that it was only used for lighting and cooking, where it had major advantages over candles and coal (Higman and van der Burgt, 2003). Even if the production of the gas caused many environmental problems, it also solved the problem posed by hazardous smoke and the risk of fires started by candles, and indoor coal and wood fires. The main advantage, however, may have been that the cost of the gas was considerably lower than candles (Falkus, 1982).

Based on the early development and use of pyrolysis gas, two different trajectories emerged. The first involved the development of the first gas engines; the second was the discovery of promising applications in the chemical industry. The developments within these two trajectories will be outlined in the following two sections. The case of Sweden will be used to capture the development of the technology for the gas engine, even though similar developments were common-place also elsewhere.

3.1.1 The development of gas engines and the case of Sweden

The positive experience from the use of producer gas gave rise to the development of the first gas-blown combustion engine, which was called an explosion engine at that time. The engine was first developed in 1881, at least ten years before the inventions of Daimler and Diesel. Modern phrases such as “gas pedal” and “step on the gas” come from this time period (Knoef, 2005).

The gas engine had a major disadvantage vis-à-vis the gasoline engine when it came to mobile applications such as transportation. The producer gas could not be stored in a feasible way and therefore had to be produced when it was used. This, together with all of the tars in the gas, which made the maintenance of the engine difficult, gave the gasoline and diesel-propelled vehicle a clear advantage. It goes without saying that the engines invented by Diesel and Daimler came to dominate the market, but the gas engine still continued to be developed.

Around 1920, some 150 manufacturers of gas engines were active and a few useful gasifiers for mobile applications appeared on the market. Experiments were conducted with gasifiers on tractors, trucks and busses in Austria, Germany and France during this time period (IVA, 1950; Knoef, 2005).

In 1923 and 1924, a few coal gasifiers from Austria were imported to Sweden to be tested on various types of vehicles. The experience with the gasifiers was generally negative. The large amount of tars in the gas clogged up the engine, which then had to be dismantled and cleaned after only 300 kilometres of use (IVA, 1950). Despite this, the Swedish military decided to further investigate how gasifiers could be used as an emergency technology to secure means of transportation in case of war. First in 1932 but also later in 1939, the Swedish government introduced incentives in the form of tax breaks and loans for people who wanted to convert their vehicles to run on producer gas. These incentives resulted in an expansion of the number of gasifiers for vehicles to about 250 units (IVA, 1950). The fast expansion of the market was followed by a backlash, however, when the public discovered that the gasifiers were of low quality, required high maintenance and, above all, were more expensive to drive (during this time, gasoline was cheap compared to charcoal).

The government reassessed the status of the programme in 1937 and found that while the quality of the gasifiers had improved considerably, there were only about 100 cars running on producer gas in Sweden. Everything changed during the Second World War, however. In 1939-1940 the price of coal fell dramatically, making running vehicles on producer gas economical again. By the turn of the year 1939/1940, there were approximately 1,000 gas cars in Sweden (IVA, 1950). When the war intensified in April 1941, strict restrictions on the use of gasoline were imposed and aggressive incentives were implemented to increase the number of cars running on gas.

The long formative phase of the technology, which had started in 1881, paved the way for ensuing rapid expansion of the market for mobile gasifiers upon the introduction of these incentives. Already by March 1941, there were 40,000 gas vehicles running on the streets and the number of gas vehicles peaked in Sweden at 71,500 in December 1941.[56]

It is still interesting to note the legitimacy that the producer gas car acquired during a very short period of time. The public's first reaction to gasification in the early-1930s was scepticism. Less than 10 years later, public attitudes were very different and people appeared to embrace producer gas vehicles. This change of heart was illustrated in 1940 by the leading motoring magazine in Sweden, *Biljournalen*, which published an issue devoted to the great experience everyone was having with gas vehicles. According to the journal, people found them easy to use, cheap to run and they allowed great freedom during the war. The knowledge base being built up around the technology was seen as a guarantee that it would prevail even after the war, when cheap oil would re-enter the market. Some problems were mentioned such as the inconvenience of having the gasifier mounted on the car and the more time-consuming maintenance involved, but the advantages clearly outweighed the disadvantages (Hilding, 1940). Despite this, cheap oil re-entered the market soon after the war and producer gas cars disappeared.

3.1.2 Gasification and the chemical industry

The most successful and durable application of gasification so far was within the chemical industry. It commenced when the 18-year-old Englishman William Perkin discovered the first coal tar dyes in 1854, and his instructor Wilhelm Hoffmann returned to Germany with that knowledge (Hatheway, 2007).

In 1900, gasification took a significant leap forward in terms of its ability to produce more complex products through the water gasification process. This was important for the

[56] The success of mobile gasifiers was not just a Swedish phenomenon. Approximately one million gasifiers using wood or charcoal were also being used to drive cars, trucks, boats, trains, and electrical generators in Europe at the time (Knoef, 2005).

chemical industry since it enabled the production of ammonia and methanol. In this new gasification process, a gas containing equal amounts of hydrogen and carbon monoxide could be produced. The carbon monoxide could be converted into hydrogen through a CO shift reaction, and the hydrogen or synthesis gas could then be used for ammonia and methanol synthesis (Higman and van der Burgt, 2003).

The process, however, was discontinuous. It was not until Carl von Linde commercialised the cryogenic separation of air during the 1920s that the process could be made into a continuous one. A flow of important innovations for improving the gasification process came after von Linde's innovation. The first break-through was the Winkler fluid bed process in 1926, which was followed by the Lurgi moving bed pressurised gasification process in 1931 and the Koppers-Totzek high temperature entrained flow process in the 1940s (Higman and van der Burgt, 2003). These innovations benefited the chemical industry and enabled it to undertake large-scale and more efficient production.

No major product innovations have been introduced for the gasification of solid fuels since the Second World War (Higman and van der Burgt, 2003). Nevertheless, gasification capacity has grown tremendously in the chemical industry. The growth of modern gasification for the production of various chemicals, transportation fuels and ammonia as a nitrogenous fertiliser started off with the wartime synthetic fuel programme in Germany and, later, the foundation of the South African Coal, Oil and Gas Corporation (Sasol). With the increasing availability of natural gas in the 1950s, the importance of coal as a feed-stock declined, although the need for synthesis gas did not. After the Second World War, the annual demand for ammonia as a nitrogenous fertiliser increased from 5.5Mt per year to 54.0Mt in 1969 and has, until more recently, been the main driver for increasing gasification capacity worldwide (Higman and van der Burgt, 2008).

It is along the trajectory of developing and producing chemical products that modern alternative fuel, heat and power from gasification has been and most likely will continue to develop. The following section will outline and analyse the market for commercial gasification.[57]

3.2 Commercial gasification, applications and markets

The two main components in the synthesis gas, carbon monoxide and hydrogen are the main building blocks for producing a wide range of products within modern chemistry. Basically, any carbon-based feed-stock such as coal, oil, peat coke, natural gas, biomass, and waste can be converted into ammonia, methanol, hydrogen, Fischer-Tropsch (FT) products, synthetic natural gas (SNG), town gas, and electricity (see Figure 3.2.1).

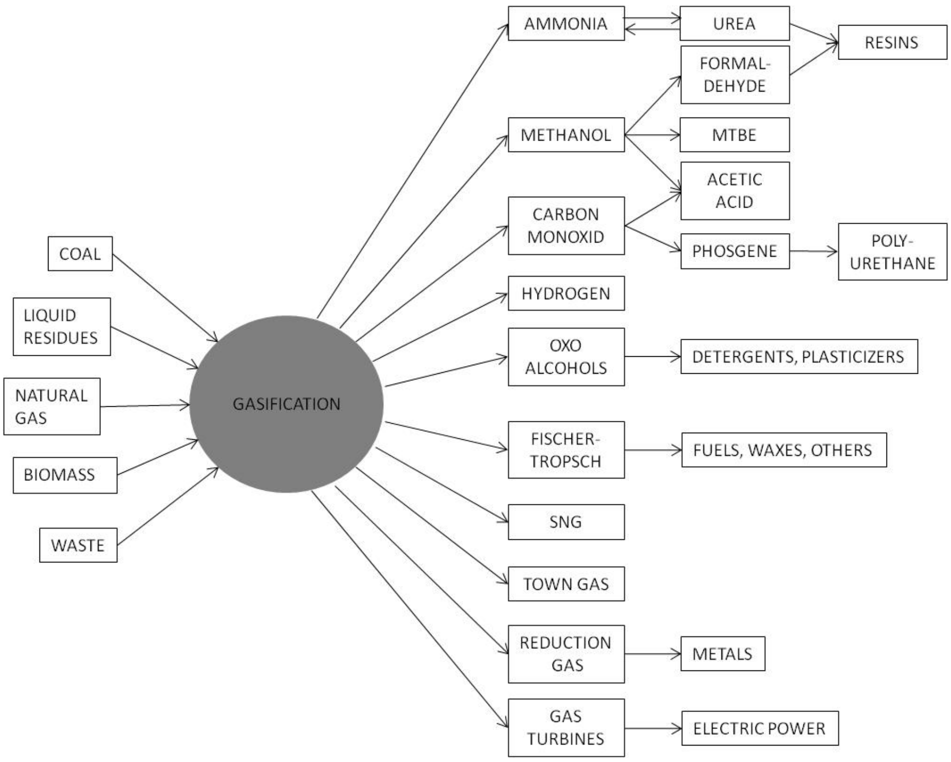

Figure 3.2.1: Applications for synthesis gas. Source: Higman and van der Burgt (2008).

[57] All of the commercial applications for combustible gas from pyrolysis or fixed bed gasification came to an end with the large-scale diffusion of electricity around 1900, and the oil and natural gas industry between 1910 and 1920. Only for a short time, during the Second World War, was the technology brought back and developed as an emergency fuel for vehicles. There are, however, still uses for pyrolysis and fixed-bed gasification for various applications. Pyrolysis is also used for the liquefaction of biomass into a bio-oil, which some actors try to develop into a usable diesel and gasoline fuel. Fixed bed gasifiers of the type used in vehicles during the Second World War are now used for rice husk gasification. It is a commercial process for electricity production and cooking gas in Southeast Asia, but suffers from too much tars and low heating value (Knoef, 2005; Zhou, 2009). Development work is being carried out in many countries to make it commercially viable for small-scale electricity production in Europe. There are currently a few plants operating fairly well, but the reliability of the process is still quite low (Lettner, 2007; Bräkow and Oettel, 2008; Kurkela, 2008). I have excluded pyrolysis and fixed bed gasification from this thesis unless the technology is directly used for the pre-treatment of biomass for the production of second-generation renewable fuels.

For both technical and economical reasons, some of these alternatives may not be possible or desirable to combine. For example, it would make little sense to produce SNG from natural gas, even if that is, of course, possible. Moreover, biomass and waste gasification is both technically and economically difficult to accomplish for producing chemicals, transportation fuels and power generation through an integrated gasification combined cycle (IGCC). Biomass gasification is, therefore, not seen as a commercially available technology, except for less advanced applications with lower demands on gas purity and in some cases for co-firing with standard coal gasification technology.[58] The specific challenges associated with biomass and waste gasification will be outlined and analysed in Section 3.3.

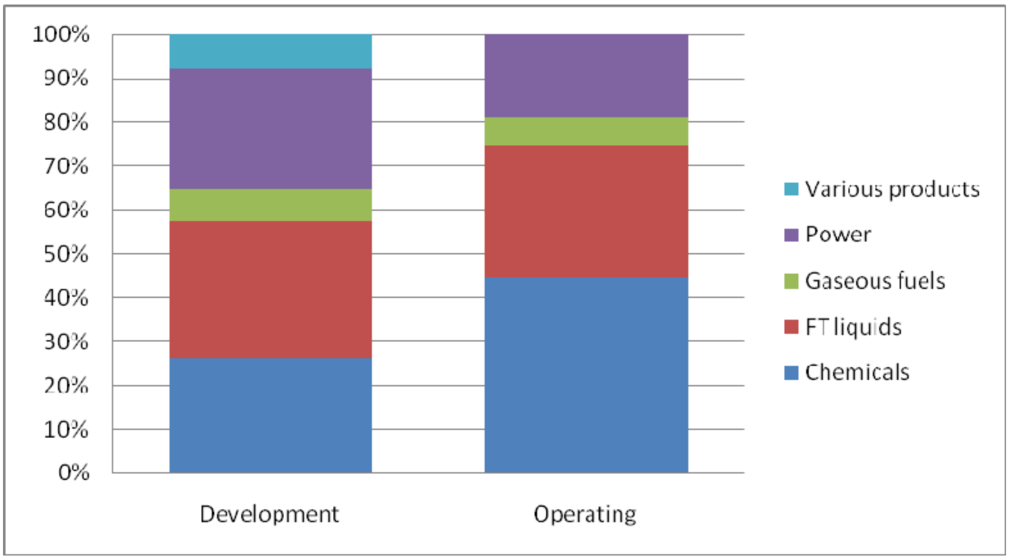

Figure 3.2.2: Accumulated currently operating and planned capacity. Source: GASIF (2007).

The total market for gasification plants has experienced strong growth since the 1950s and is projected to continue to grow in the near-term future (see Figure 3.2.2). During this time frame, three major trends can be discerned.

The first concerns FT liquids, which have increased in production considerably since the beginning of the 1970s and is predicted to continue to do so. Around 1990, about half of the

[58] There are good reasons for producing more than one product from the same source of syngas and for enabling its production from multiple feed-stocks (i.e., co-firing). With such a flexible set-up, the operator can shift to the cheapest feed-stock and increase production of the product with the highest market value at any given time. The security of supply would, thus, be improved for both the operator of such a plant and its customers (Higman and van der Burgt, 2008).

world's gasification capacity constituted the production of FT liquids. The installed capacity originates from Sasol's three facilities for converting coal to FT liquids in South Africa, and one plant in Malaysia based on natural gas, which was built by Shell. Sasol increased their production extensively in the mid-1970s to the mid-1980s and remains the largest gasification centre in the world (Higman and van der Burgt, 2003). In 2007, 50 percent of the total coal used for gasification was used for FT synthesis at the three facilities in South Africa, operated by and based on Sasol coal-to-liquids (CtL) technology.

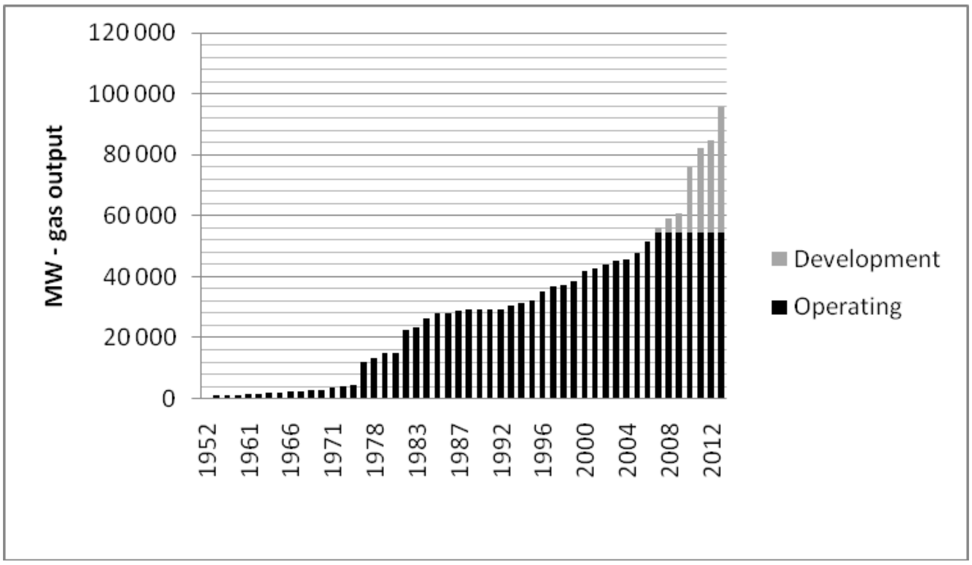

Figure 3.2.3: Product distribution, operating gasification plants and planned capacity. Source: GASIF (2007).

The production of FT liquids is expected to increase dramatically sometime after 2010, when the extremely large (10,936MW_{th}) Pearl Gas-to-Liquids (GtL) plant in Qatar may come online. The plant accounts for 27 percent of all planned capacity until 2012, according to GASIF (2007) (see Figure 3.2.3). When completed, it will be the single largest gasification plant ever constructed. With the completion of the plant, the share of FT liquids of the total output of products from gasification will be maintained at about 31 percent (see Figure 3.2.3).[59] Not included in the GASIF (2007) statistics are an additional 18 projects that have been reported to be under development in China for the production of liquids through the gasification of coal. If these projects are realised, FT liquids production would increase by an additional

[59] Calculated in terms of MWh_{th} syngas used for the various applications.

2,755 thousand barrels per day by 2020 (Périneau, 2009). However, coals to liquids projects in China have become highly controversial, since coal is relatively scarce in China in relation to the current use and production requires large quantities of water, of which very little is available in the regions where the plants have been planned to be built. Consequently, the National Development and Reform Commission has approved only a few of the proposed projects, and is unlikely to approve more in the near future (Fang, 2009).

The second trend concerns the increasing share of coal-based gasification for power production. The integrated gasification combined cycle (IGCC) turns coal into a syngas that can be passed through a combined cycle gas turbine for power production. The rationale for developing the technology has been to increase electrical efficiency and environmental performance compared to conventional coal boilers. With the technology, the flue gas can be cleaned of sulfur dioxide, particulates, mercury and other unwanted components in the coal at the pre-combustion stage at a lower cost than conventional post-combustion cleaning. The technology also allows for carbon capture, during which the CO_2 can be separated, compressed and stored away (CCS).[60] In total, 11,000MW_{th} (27 percent) of coal-based IGCC capacity is planned between 2007 and 2012 (GASIF, 2007) (see Figure 3.2.3).

The third trend involves what is expected to be a rapid increase in the production of chemicals from coal in the period beyond 2007. According to GASIF (2007), 26 percent of the planned capacity will be new chemical plants. Of these chemical plants, 70 percent are planned to be built in China and almost 90 percent of these will be based on coal. The chemical plants in China mainly produce ammonia for nitrogenous fertiliser and methanol. In addition, there is at least one plant now in operation constructed by Shell for the Shenhua Coal Liquefaction Corporation in Inner Mongolia with a capacity of 4,000 tonnes per day (t/d) for the production of hydrogen used for liquefying coal in the production of transportation fuels and chemicals (Chhoa, 2005).

[60] In the US, an increasing number of states require all new coal plants to be "carbon capture ready". However, in reality few plants will use carbon capture and storage (CCS) technology, since there is currently no general legislative framework supporting the technology, and the available CCS technology would increase the cost of electricity production considerably (Holt, 2007; Renzenbrink et al., 2007).

The three applications of FT liquids, power and chemicals, constitute 90 percent of total operational and planned conversion capacity. Production of chemicals and FT products has been and continues to be the largest application, with 45 percent and 30 percent of the total capacity currently operating. Power production amounts to 19 percent of all installed and operating capacity. Currently, 32 percent of installed capacity is oil-based and 55 percent is coal-based. However, only 4 percent of the planned capacity will use oil as the primary feed-stock. Instead, coal will strengthen its position and the use of natural gas will increases from 8 to 16 percent, if all the currently planned capacity is realised by 2012. Seventy-five percent of the planned and currently operating capacity has been concentrated in four countries that are either rich in coal or off-grid gas: USA (27%), China (21%), South Africa (16%) and Qatar (11%).

In total, there are 140 operating gasification plants and some 411 reactors in the world, with a total syngas output capacity of 54GW_{th}. In addition, 31 plants with a total capacity of 41GW_{th} have been planned for coming online by 2012 (GASIF, 2007). The average size of a single gasification reactor is approximately 135MW. The average plant size varies significantly depending on which type of product produced. FT plants are considerably larger than both chemical and power plants. As mentioned above, there are only four FT plants operating in the world, three in South Africa and one in Malaysia. In total, these four plants use 103 gasifiers and the capacity of the plants range from 1,000MW_{th} to 7,000MW_{th}.[61] There are 97 chemical plants currently operating with an average size of 250MW_{th}. In comparison, there are currently 23 IGCC power plants operating with an average capacity of 440MW_{th} (GASIF, 2007). Plants that produce FT liquids are thus considerably more dependent on economies of scale to make their products competitive on the market.

The capital goods sector supplying gasification technology is heavily concentrated in three actors, General Electric, Sasol Lurgi and Shell. Their combined market share increased from 88 to 93 percent between 1999 and 2007. Roughly a dozen other technology suppliers provide gasifiers, but their combined share has been nearly halved over the same time period (GASIF, 2007). Among the three main competitors, Shell was the smallest in 2007 but

[61] The plant in Qatar will be the largest in the world and have a total thermal capacity of 11,000MW_{th}.

was expected to experience the strongest growth in the near future, since it will supply gasification and downstream technology for the Pearl Qatar GtL project. In addition, in 2005 Shell was reported to have signed another 12 contracts for coal gasification projects in China (Chhoa, 2005). As a result, it is expected to increase its market share from 28 percent in 2007 to 45 percent by 2010, while Sasol Lurgi's share is projected to decline from 34 to 25 percent and GE's from 31 to 24 percent.

Of these major companies, it is only Sasol Lurgi that has some experience with processes dedicated for biomass and waste gasification. Shell and GE have, so far, only developed their gasification technologies for fossil fuels.[62] Three of the actors with small market shares (TPS[63], Foster Wheeler and Envirotherm) have experience in biomass or waste gasification, while the remaining actors primarily compete with the big three in coal gasification. Sasol Lurgi and Shell are also the only actors that have commercial experience with FT synthesis (GASIF, 2007).

In conclusion, fossil gasification is a mature technology. It has proven to be both an attractive and versatile process through which virtually any carbon-based material can be turned into a valuable product such as chemicals, transportation fuels, town gas, and electricity. The market growth is, however, exclusively focused on fossil fuels, and the capital goods sectors supplying gasification technology have been heavily concentrated in three main actors. As of yet, these actors have shown very little interest in the gasification of renewable resources such as biomass and waste residues. The following section will outline the main technical challenges for realising such combinations.

3.3 Technical challenges, past and potential markets of biomass gasification

Given the debate on climate change, there has been a growing interest in developing alternative fuels using biomass as a feed-stock. To some extent, biomass gasification can draw upon the knowledge base of fossil fuel gasification.

[62] However, Shell has demonstrated up to thirty percent biomass co-feeding in the Buggenum IGCC plant (Zwart, 2007).

[63] The company TPS has filed for bankruptcy and is no longer active.

However, the physical and chemical properties, as well as the availability and spatial concentration of biomass, are distinctly different from coal and oil. As such, fossil fuel gasification systems have been designed in such a way that they cannot be used for biomass gasification without major modifications of the entire system. For example, all fossil alternatives have considerably higher heating values and are chemically more homogenous, compared with the low heating value and chemically heterogeneous character of biomass. In addition, most coals can easily be ground into a fine powder or be made into a slurry and, just like oil or natural gas, can be easily fed into the gasification reactor at high pressures. In contrast, biomass consists of long wood fibres that are not well-suited to current reactor designs. The biomass resource is also different from fossil fuels in that it is geographically distributed, while fossil fuels can be found in large quantities in specific areas, making collection and distribution more efficient. The lower heating value of biomass also makes transportation of large volumes costly. However, this latter problem should not be over-emphasised since there is a global trade of untreated biomass and it can be found processed in large quantities at paper mills.

In order to turn biomass gasification into a commercially viable process for the production of chemicals, transportation fuels and electricity generation (IGCC), the development of the technology has progressed along three main trajectories (see Figure 3.3.1). To various extents, these trajectories draw upon existing knowledge of fossil gasification and biomass combustion. However, for the technology to succeed producers must also develop knowledge specific to the field of biomass gasification and the trajectory they have chosen

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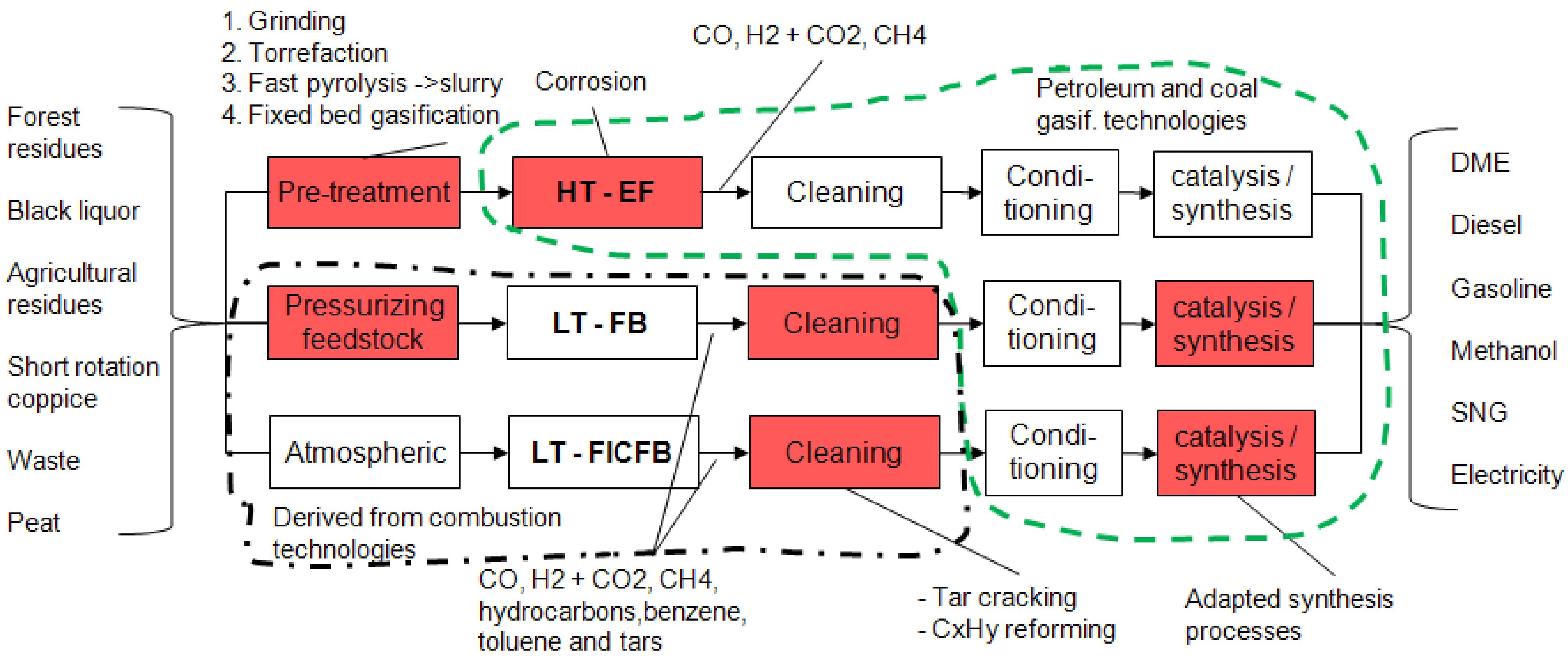

Figure 3.3.1: Three trajectories toward biomass gasification (High Temperature (HT), Low Temperature (LT), Entrained Flow (EF), Fluidised Bed (FB), Fast Internal Circulating Fluidised Bed (FICFB))

The trajectory of Entrained Flow (EF) gasification draws primarily on technologies and competencies that have been developed for oil and coal gasification. The trajectory constitutes the ability to gasify biomass under high temperatures, high pressure and on a large-scale. The process results in a relatively clean syngas (consisting mainly of carbon monoxide and hydrogen), which after some modest downstream processing can be synthesised, based on existing coal technologies, into advanced chemicals or transportation fuels, or can be used to produce power in a combined steam and gas cycle (IGCC). In the case of biomass, the downstream processes can be more or less based on existing coal technologies.

As previously mentioned, EF reactors were not developed for the physical or chemical properties of biomass, and as such it is necessary to develop a complementary pre-treatment system. Such systems are currently not commercially available. A potential problem with the process is that high temperature gasification consumes more of the feed-stock than low temperature gasification. As a result, the overall efficiency of the process may be lower, unless the syngas can be used for electricity production in a combined cycle. As illustrated in Chapter I, the efficiency of biomass conversion greatly influences the overall substitution potential of second-generation fuels.

The two other trajectories originate from the field of combustion and operate at a lower temperature than EF gasification (<1000 degrees Celsius): pressurised fluidised bed (FB) and atmospheric fast internal circulating fluidised bed (FICFB).[64] The pressurised FB system must be oxygen-blown, which significantly increases investment costs, and can be operated on a large-scale when the production of synthetic fuels is intended. For power production, an oxygen source is not necessary and the atmospheric process (FICFB) can possibly be operated on a smaller scale also without an external oxygen supply for the production of synthetic fuels.

Since the fluidised bed technology has been extensively used for biomass combustion it is well-suited to the physical and chemical properties of biomass. Feeding biomass into the

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[64] This trajectory could also have been described as "steam gasification" to include the SilvaGas process from the US. However, the projects currently pursued in Europe are based on the FICFB technology developed in Austria (see Chapter V).

gasification reactor, therefore, poses no problem. However, these systems normally operate under atmospheric pressure and there is little experience with pressurised feeding systems.[65] In addition, the gas is contaminated with varying levels of tars, alkaloids, hydrocarbons, benzene, nitrogen, toluene, and other contaminants. In less advanced applications for biomass gasification, such as co-firing with coal, gas purity requirements are moderate and the contaminants do not necessarily pose a problem. As the focus shifts to transportation fuels, an *ultra clean* gas is required of the same quality that is achieved from the high temperature route (Boerrigter and Rauch, 2006). As such, producing a transportation fuel means that a set of additional competencies related to the cleaning, and catalysis of the product gas is required.

A basic gasification system can thus be divided and analysed based on sets of inter-related knowledge fields: (1) pre-treatment of the feed-stock, (2) the gasifier, (3) cleaning and conditioning of the raw gas, and (4) the application of the gas (see Figure 3.3.1). If gasification is to be successful, it is important to design the entire system as an integrated unit in which the inter-related knowledge fields are developed and applied, taking into careful consideration which type of biomass feed-stock is going to be used and the final product(s) of the process. Ultimately, it is the final application that determines the gas quality requirements.

The different types of biomass resources available and the four inter-related knowledge fields in a biomass gasification process will now be described and analysed. The descriptions will be brief and describe only the most important inter-relationships. For more detailed descriptions of gasification see, for example, Knoef (2005) or Higman and van der Burgt (2008).

3.3.1 Feed-stocks and pre-treatment

The first part of the gasification system deals with the feed-stock and its eventual pre-treatment before gasification. As a feed-stock, biomass resources are versatile in nature and

[65] The experience from Värnamo in Sweden (Chapter VII) and Oulo, Finland (Chapter VIII) illustrates that it is possible.

consist of many different liquid, woody and non-woody resources, including wood and forest residues, black liquor, agricultural residues and waste streams (see Figure 3.3.1).

Large volume residues are generated, for example, by the forestry and wood processing industries, in the form of thinnings, barks, roots, branches, and saw dust. The residues can easily be made into wood chips or pellets that are suitable for gasification.

Another potentially important feed-stock suitable for gasification is black liquor, which is a by-product from the industrial process of chemically digesting pulpwood. Black liquor contains the inorganic chemicals used in the process but also half of the energy content of the wood fed into the digester, and can potentially become an important feed-stock for gasification.[66] However, it is highly corrosive and involves very specific technical challenges for which a new type of reactor design has been developed (see Chapter VII).

The above-mentioned biomass-based feed-stocks are, however, limited to a few countries with extensive forestry industries such as Sweden, Finland and Austria (Lehtinen et al., 2004). For countries like Germany, agricultural residues such as straw and other types of non-woody biomass can potentially become important feed-stocks for gasification. Significant volumes of such residues are unused today, or have little economic value. However, straw has a very low energy density. It has been estimated to have in the range of only 13 to 33 percent the energy density of woody, solid types of biomass such as forest residues (Matsumura et al., 2005; Higman and van der Burgt, 2008). Straw's low energy density makes it costly to transport.

A third resource potential available for gasification in large quantities is various types of waste streams, commonly used for heat and electricity production. One such waste stream is referred to as refuse-derived fuel (RDF) and is produced by sorting, shredding, dehydrating and sometimes pelletising household and industrial waste. Depending on the actual content of the RDF and the legislative framework in different countries, these sources are classified as either a waste or a biomass resource. How they are classified is important for what type of incentive structures and regulations investors and plant operators have to comply with

[66] The energy content removed from black liquor to make, for example, transportation fuels must be replaced elsewhere in a pulp and paper mill to keep the energy balance intact.

(Kivelä and Takala, 2009). For gasification, however, these types of fuel pose problems in terms of varying energy densities and the existence of different chemical compounds and metals that can be difficult for the gasification process to handle.

A fourth and final type of biomass that could potentially be made available for the use of biomass gasification is various types of short rotation coppice (SRC) on unused farm land such as poplar and willow. This feed-stock poses similar challenges as other woody biomass fuels and is easily made into wood chips.[67] Its overall biomass potential will be outlined in the subsequent section of this chapter.

Depending on the type of gasification process used (EF or FB), the above-mentioned feed-stocks need to undergo more or less pre-treatment before they can be fed into the gasifier. The most demanding type of gasifier in terms of specifications on the feed-stock is the entrained flow reactor, since it can only handle slurries or powders with particle sizes of the order of magnitude of 500 µm (Higman and van der Burgt, 2008).

It has been argued that traditional cutting and grinding of biomass to such small sizes is difficult and costly in terms of energy use (Knoef, 2005; Zwart et al., 2006b; Nordin, 2008). There are currently four main trajectories under development to solve this specific problem. The trajectories both complement each other and compete with each other, since some are better at processing one type of feed-stock than the other (although there are also overlaps).

The first trajectory is based on existing experience with the large-scale grinding of biomass into a fine powder from the pulp and paper industry, which developed the technology during the 1970s. The technology is currently being further developed and tested in combination with EF gasification (Gebart, 2008; Persson, 2008; Energimyndigheten, 2009a).

The second and third alternatives are torrefaction and fast pyrolysis, both of which are based on a mild thermal pre-treatment of the biomass. In torrefaction, biomass is heated to

[67] In addition, peat can be harvested and used for biomass gasification in a few peat-rich countries such as Canada, USA, Finland, and Sweden (Spedding, 1988). However, since peat has often been described as “coal in the making” and is not replaced at the same rate at which it is used, there are genuine questions about whether peat should be counted as a renewable resource (Spedding, 1988; Schilstra, 2001).

a temperature in the range of 200-300 degrees Celsius, in the absence of oxygen. After such treatment it can—easily and at low energy costs—be turned into a coal-like powder with small particle sizes and still retain 83-97 percent of the energy in the fuel (Bergman et al., 2005). Through fast pyrolysis, the biomass can be turned into a combustible liquid with high energy density—half of the energy density of oil but up to 10 times that of the original biomass. In the pyrolysis reaction, the biomass is decomposed to a liquid at a reaction temperature of 500 degrees Celsius, with a short vapour residence time (less than two seconds) and rapid cooling of the pyrolysis vapours to generate the slurry (Bridgwater et al., 1999; Bridgwater, 2007).

The fourth type of pre-treatment of the biomass currently under development in combination with an EF reactor is the use of fixed-bed gasification. The fixed-bed gasifier is used to heat the biomass to 400-500 degrees Celsius, at which point it is broken down into tar-rich volatiles and solid char before entering the EF reactor (Rudloff, 2008b). The fibrous structure of the biomass is destroyed in this process and the char can be milled conventionally.

These types of pre-treatment systems have only been tested on a small-scale, and there is limited experience with integrating them in complete gasification systems. The systems can, therefore, not be considered commercially proven at this point. As a consequence, there is a lack of specialised suppliers for the above-mentioned technologies. The emergence of such suppliers is, however, essential for the emergence of an industry with a capacity for realising the potential of biomass gasification.

3.3.2 Reactor processes and designs

Fluidised bed (FB) and entrained flow (EF) are the two main reactor designs considered for the production of alternative fuels. The basics of these two processes will now be outlined (see Figure 3.3.1).

The basic principle of the FB is that the gasifying agent, which can be steam, air or oxygen, enters the bottom of the gasifier at a velocity of 2-10 m/s and at a low temperature (<1,000 degrees Celsius) (see Figure 3.3.2). The process is also referred to as low temperature gasification. As noted earlier, the lower temperature increases the contamination of the gas, particularly through the higher concentration of tars, but also with CO_2, H_2O, C_xH_y aliphatic hydrocarbons, benzene, and toluene (Boerrigter et al., 2005). Even if the higher concentration of tars is measured in as little as tens of grams per cubic metre of gas, together with other contaminants they pose a problem in the gas cleaning and conditioning processes if the gas has to be upgraded to a syngas and used for advanced applications.

In the fluidisation process, the velocity of the entering agent is adjusted so that the fuel, in combination with a bed material (usually sand), becomes suspended over the bottom of the gasifier. In this suspended state the fuel behaves as a fluid, hence the name fluidised bed. There are two basic types of fluidised bed gasifiers: bubbling fluidised bed (BFB) and circulating fluidised bed (CFB) (see Figure 3.2.2).

In the BFB, the oxidant enters the bottom of the gasifier through a bed of sand. The speed of the oxidant is important since it influences the size and speed of the bubbles which, in turn, influence the mixing and heat exchange between the fuel particles (Olofsson et al., 2005). The raw gas exits at the top of the gasifier through a cyclone that separates sand and fly ash from the raw gas. The same basic principle is applied in the CFB, with the difference being that the oxidant enters through the bottom of the bed at a higher velocity. This higher velocity reduces the bubbling character of the bed and creates more flying sand and feed-stock, which in turn allows for greater mixing. The fly ash, sand and particles captured in the cyclone are, therefore, circulated to the gasifier at much greater quantities than in the BFB.

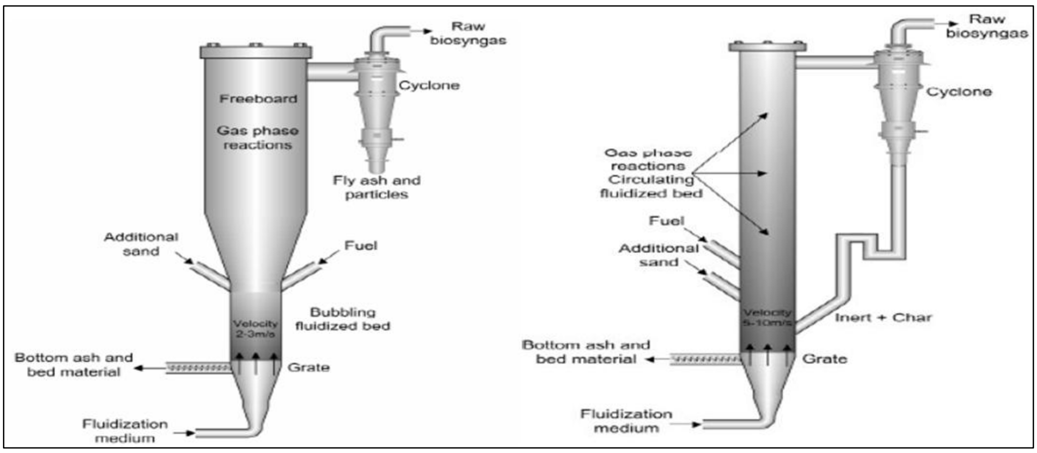

Figure 3.3.2: Schematics of a bubbling and a circulating fluidised bed. Source: Olofsson et al. (2005).

In the fluidised bed process, heat can be supplied to the gasification process either directly or indirectly. During direct gasification, part of the feed-stock is combusted to provide the necessary amount of heat. This is the most commonly used approach: an alternative is to transfer the heat from an external source, such as steam, through the gasification agents. This process is called indirect gasification, or the fast internal circulating fluidised bed process (FICFB). It operates at atmospheric pressure and the design eliminates the levels of nitrogen in the product gas, increases the amount of methane[68] and, thus, also the energy content.[69] It is an alternative design that excludes oxygen as a gasification agent for advanced applications, reducing the cost of construction and operation.

The two fluidised processes mentioned above are well adapted to the physical and chemical properties of various types of biomass and advanced pre-treatment is generally not necessary. However, pressurising the feed-stock may pose a challenge depending on its target application.[70] There has been some experience with various designs of lock-hopper and screw-based systems, which have achieved pressure of between 10 and 20 bars (Blackadder et al., 1992; Sydkraft, 1997, 2000; Salo, 2008).

The other type of reactor is the Entrained Flow (EF) gasifier. In the EF gasifier, fuel in the form of slurry or pneumatically transported fine particles is injected into the top of the gasifier, normally at high pressure (see Figure 3.3.3). The feed-stock is mixed with oxygen

[68] The high content of methane in the gas makes the FICFB process attractive for SNG production, which unlike most other synthesis processes can be operated at atmospheric pressure (Zwart et al., 2006a; Hofbauer, 2007).

[69] Depending on the desired application, the gasification agent can be either steam in a combination with oxygen or air. If air is used, the amount of nitrogen in the gas increases and it cannot be used in synthesis applications such as for Fischer-Tropsch diesel, methanol, DME or SNG. Using pure oxygen enhances gas quality, eliminating the nitrogen component, but oxygen is costly to produce.

[70] The gasification process can be performed under different pressures ranging from 1-80 bars. Pressurising the feed-stocks before injecting the gasifier has several benefits. Firstly, with increased pressure, the size of the plant (number of MW) can be increased in relation to the amount of material that is needed to construct it. The benefits of compact design are reached at a maximum of 15-25 bars of pressure. With higher pressure, little additional reduction of plant size in relation to costs can be achieved (Higman and van der Burgt 2003 p.17). It may, however, be beneficial to pressurise the feed-stock even further since it uses significantly less energy than pressurising the gas exiting the gasifier. The optimal gasification pressure also depends on which gas cleaning, conditioning and final application the plant is optimised for. For example, the synthesis process for producing DME, Methanol or FT diesel requires the gas to be at a pressure of about 60 bars. Ammonia synthesis requires a pressure of about 200 bars. Gasturbines run at 20-40 bars of pressure (Higman and van der Burgt 2003 p. 17-18). For other applications such as SNG production, it has been argued that the methane synthesis can operate at atmospheric pressure and pressurised gasifier may therefore be a disadvantage (Hofbauer 2007) (see Chapter V). However, it still needs to be proven, since the only currently operating SNG plant in North Dakota operates at high pressure (Higman, 2010).

and steam and converted in a turbulent flame. The reactor operates at high temperature (>1,200 degrees Celsius) and with a very short reaction time of less than ten seconds. The high temperature gasification results in a gas that primarily contains the two combustible components hydrogen (H_2) and carbon monoxide (CO), as well as low levels of tars, nitrogen or other contaminants. Since it operates at a very high temperature, a lot of sensible heat[71] is produced. This heat needs to be used in power applications if the efficiency of the process is not to be decreased (Higman and van der Burgt, 2003).

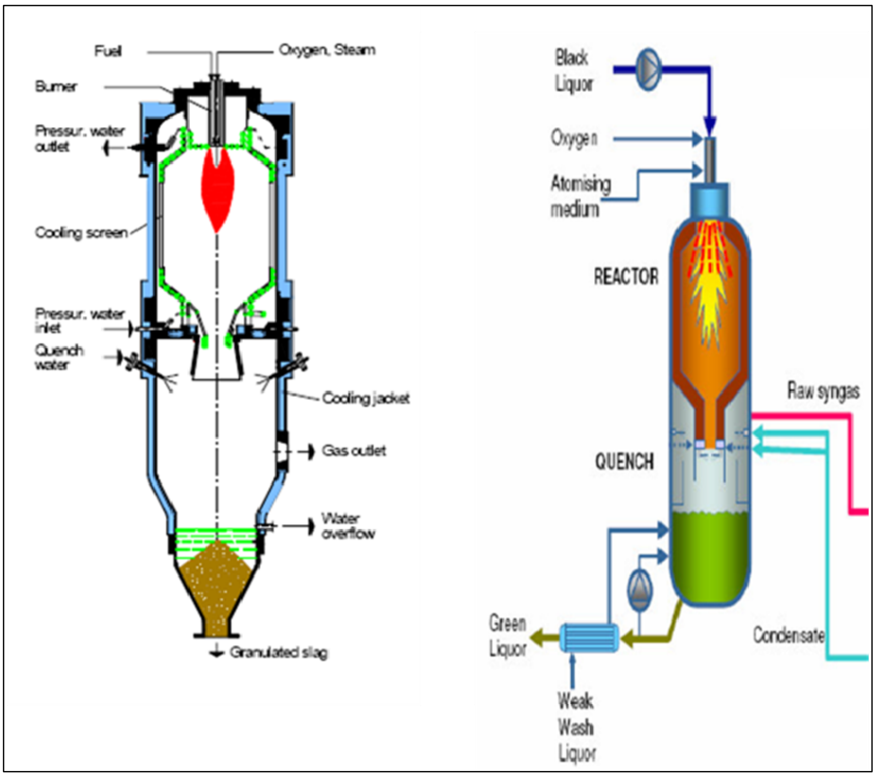

Figure 3.3.3: The GSP and Chemrec entrained flow reactors. Source: Siemens and Chemrec.

So far, only two types of EF reactors have been tested with biomass-based feed-stocks (however, see also FZK/Lurgi in Chapter VI). The first reactor, called GSP, was specially developed and designed for the corrosive type of lignite available in the eastern part of Germany, a corrosive character that it shares with the bioslurries produced through fast pyrolysis. The reactor is equipped with a screen that protects it from the extensive corrosion that would otherwise occur. Extensive pilot tests based on the GSP have been undertaken

[71] The quantity or magnitude of sensible heat is the product of the body's mass, its specific heat capacity and its temperature above a reference temperature.

with various type of pre-treated biomass, but the entire chain from feed-stock to end product has so far not been demonstrated.

The Swedish company Chemrec has developed a reactor with a ceramic lining that is specially designed to withstand the extremely corrosive character of black liquor. Both types of gasifiers can be operated under high pressure and should be able to be integrated with the standard downstream process developed for commercial fossil gasification, even if this has not yet been demonstrated on a large-scale.

In conclusion, compared to fluidised beds, EF gasifiers produce a superior quality of gas in terms of the amount of tars and contaminants within. However, with the exception of black liquor gasification, there are no commercial pre-treatment systems available. In addition, they consume more energy and the efficiency can therefore be hampered if the gas is used for producing synthetic fuels. The fluidised bed gasifiers have, on the other hand, more contaminants in the gas but also a higher usable heating value. The higher methane content in the gas makes it suitable for SNG and electricity applications. The gasifier is easy to feed at atmospheric pressure with a wide variety of biomass feeds. The down-side of fluidised bed gasifiers is that gas cleaning can become costly and pressurising the feed-stock is difficult. The basic problems of gas cleaning will now be expanded on.

3.3.3 Cleaning and conditioning of the raw gas

The raw gas from all type of gasifiers needs to be cleaned and conditioned before it is used in any type of application (see Figure 3.3.1). The process involves getting rid of impurities such as tars, particles, halogens, alkali metals, S-compounds, N-compounds, heavy metals, and calcium, processing to adjust the H_2/CO ratio, reforming methane (except for SNG application) and, in some cases, reducing the fraction of CO_2 (Olofsson et al., 2005). As already mentioned, gas cleaning associated with high temperature gasification is a relatively straight-forward process and commercial technologies are available on an industrial scale.[72] This section focuses on the problems associated with low temperature gasification for

[72] For an overview of the commercially available techniques and processes that are used for cleaning the raw gas from high temperature gasification, see Higman and van der Burgt (2008).

advanced applications such as FT liquids, methanol, DME, SNG synthesis and, perhaps to a lesser extent, IGCC.

The technologies used for tar removal can be divided into two categories: primary and secondary methods (Devi et al., 2003). Primary methods deal with lowering the tar content of the gas exiting the gasifier through the proper selection of operating parameters, the use of bed additives/catalysts and gasifier modifications. According to Devi et al. (2003), it is possible to reduce the dependency on downstream cleaning with primary methods, which still can be developed further.

All gasification processes for advanced applications use extensive downstream, secondary cleaning methods. These methods consist of the physical removal of tars with wet scrubbers, electrostatic precipitators, barrier filters, and cyclones, as well as the catalytic or thermal destruction of tars (Devi et al., 2003; Iversen and Gøbel, 2005). The secondary methods can be applied successfully to clean the gas of tars, but the cost of gas cleaning increases with the number of secondary methods that are used.

The low temperature gasification projects analysed in this thesis (an overview of the project will be provided in Chapter 3.4) use both primary and secondary methods to produce a clean gas from low temperature gasification for advanced applications. One such project is the Güssing plant in Austria where a clean synthesis gas has been produced from an indirect, low temperature, atmospheric fluidised bed gasifier. Through synthesis the gas has been converted to SNG and FT diesel. It has also been tested to run a fuel cell (Aichernig et al., 2004; Hofbauer, 2007).

Although the production of a synthesis gas can be accomplished on the scale of a pilot or in a small demonstration plant, this does not imply that the processes can easily be replicated on a larger scale. When the biosyngas from low temperature gasification is intended for synthesis applications, the integrated process, which includes gas cleaning and synthesising, has not been proven on a commercial-scale. Some of the projects studied in this thesis attempt to solve this problem by experimenting with a range of methods for both improving gas quality and adopting conventional synthesis technologies. Various technology suppliers may exist for some of the individual components needed. However, a much larger problem is that there are currently no suppliers with industrial experience in combining the necessary cleaning systems for low temperature gasification with the required synthesis technologies.

3.3.4 Past and potential applications for biomass gasification[73]

Syngas from biomass can potentially provide value in the same type of applications as syngas derived from fossil fuels. However, the technology can only be considered ready for use in a few less advanced applications and perhaps even in fewer where it currently makes economical sense.

Biomass gasification can be seen as a stand-alone process, but the product gas or syngas derived from biomass could also be co-fired in combination with gas from fossil resources in some of the applications. In such an application, renewable and fossil-based feed-stocks can be mixed prior to gasification, or the gases can be mixed following the gasification but consumed in an application. The amount of gas cleaning is determined by the requirements of the end-application. As the gas requirement becomes increasingly strict, the application becomes more advanced. This section presents the existing co-firing and stand-alone applications. Their actual market potential will be presented in the subsequent section.

Boiler, Cement and Lime Kilns

The least advanced use of the product gas from biomass gasification is to fire it in a boiler or in a kiln used in the cement or pulp and paper industry. The kiln application was developed for oil substitution in the early-1980s largely by two major and competing technology suppliers to the pulp and paper industry: Götaverken from Sweden and Ahlström from Finland. In total, eight plants were installed between 1983 and 1987, and most of them are still in operation (see Table 3.3.1).

[73] "In order to create an overview of all capital goods suppliers and applications for biomass gasification, a database was constructed, including the major pilot, demonstration and commercial gasification plants that had been constructed or were commenced between 1970 and 2007. The database was compiled from data made available in various publications and online databases. The main data sources were IEA task 33: Thermal Gasification of Biomass - Babu (1995, 2005, 2006) and IEA (2001). Additional data came from GASIF (2004), Knoef (2005), Kurkela (1989, 2002), Palonen (2006), Larson et al. (2003; 2006), Olofsson et al. (2005), Marbe (2005), and the online database: gasifiers.org. As a result, a relatively comprehensive database with 123 entries could be constructed with what is believed to be the major plants aimed for technology development and commercial operation that have been constructed in the world. It also includes a large number of fixed bed gasifiers excluded from this study, as well as small pilot plants. However, the data is obviously skewed towards Europe and USA, since almost all data has been published by European and American authors with a focus on their contexts" (see Chapter IV). The entries concerning the main biomass gasification demonstrations and commercial projects are presented in Tables 3.3.1-3.3.5 and Figure 3.3.4.

Table 3.3.1: CFB lime kiln gasifiers.

Located in		Supplier	Operational	MW_{th}
Pietarsaari	Finland	Ahlstrom/FW	1983	34
Jakobstad	Finland	Ahlstrom/FW	1983	35
Norrsundet	Sweden	Ahlstrom/FW	1985	25
Pöls	Austria	Lurgi	1985	27
Iberian Peninsula	Portugal	Ahlstrom/FW	1986	17
Karlsborg	Sweden	Ahlstrom/FW	1986	27
Rodao	Portugal	Ahlstrom/FW	1986	15
Värö	Sweden	Götaverken/Metso	1987	30
Rüdersdorf	Germany	Lurgi	1996	100

However, after the oil crises ended in 1986, interest in oil substitution disappeared. Since then, only one additional plant was built, by Lurgi in 1996 (Hofbauer and Knoef, 2005). The technology can be considered commercial and profitable at an oil price of approximately $70-80 per barrel (2009) (Saarivirta, 2008; Isaksson, 2009).

Boiler and Co-fire

One step up the scale towards increasingly advanced applications involves firing the gas in a boiler for heat and electricity production. If the gas undergoes some cleaning before entering the boiler, it is possible to produce energy at higher steam temperatures and pressure values. This will result in higher electrical efficiency than in units based on direct combustion technologies (Palonen et al., 2006). The increased electrical efficiency compared to combustion is, however, modest unless it involves more difficult fuels such as RDF and household waste; the alternative process is waste incineration.

So far, two stand-alone plants have been built, one in Varkaus, Finland by Foster Wheeler, and the other in Chinati, Italy by TPS. The plant in Finland operates on industrial waste containing polyethylene plastics and aluminum, which would be very difficult to incinerate using conventional technology (Palonen et al., 2006). The plant in Italy operates on pelletised RDF, containing 60 percent paper and 40 percent plastics (Knoef, 2005).

Table 3.3.2: Boiler, stand alone and co-fire gasifiers.

Located in		**Supplier**	**Operational**	**MW_{th}**
Greve, Chinati	Italy	TPS	1992/1998	30
Varkaus	Finland	Foster Wheeler	2000	40
Lahti	Finland	Foster Wheeler	1998	60
Geertruidenberg	Netherlands	Lurgi	2000	85
Ruien	Belgium	Foster Wheeler	2002	50

An additional three plants of this type have been built, but with co-firing of coal (see Table 3.3.2). In the co-firing application, the product gas is cleaned before entering a coal-fired boiler where it is co-combusted. It is a potentially attractive application since existing coal plants can be complemented with a gasification unit and decrease their CO_2 emissions without the cost of completely new infrastructure (Hansson, 2009). Today, these types of plants can be constructed on a large-scale, commercial basis, but interest in the technology from customers has been modest (Palonen, 2008). Recently, there has been renewed interest in the technology based on waste gasification; in 2009 Metso Power was awarded two large contracts, in Lathi and Västerås, worth €150-200 million (Metso, 2009; MälarEnergi, 2009). If constructed, the waste gasification plant in Västerås will be the largest ever built, with a thermal fuel capacity of 200MW.[74]

Combined heat and power (CHP) with gas engine

A technically successful application for biomass gasification is combined electricity and heat production (CHP) with a gas engine. The application has been considered to be suitable when connected to a small- to medium-scale district heating system, where conventional combustion plants have considerably lower electrical efficiency.

Each gas engine has a size of approximately 1.5MW_{th} and can be connected into a series for increased capacity. They can normally handle different types of gas qualities and reasonable amount of contaminants. However, some specifications are stricter if an engine exhaust catalyst is used (Iversen and Gøbel, 2005).

[74] The project was, however, discontinued in February 2010 (MälarEnergi, 2010).

Table 3.3.3: Combined heat and power generation with gas engine.

Located in		Supplier	Operational	MW_{th}
Güssing	Austria	Repotec	2002	8
Skive	Denmark	Carbona	2008	28
Oberwart	Austria	Ortner	2009	10

So far, only three plants have been constructed (see Table 3.3.3) and it has been argued that the price of electricity, in light of the additional investment costs, reduced availability of the plant and the increased cost of raw material for gasification over combustion, makes most of these plants uneconomical at the moment (Bolhàr-Nordenkampf 2007). Nevertheless, in Germany and other countries that have adopted special support schemes for biomass electricity, there are added incentives for innovative biomass-based technologies, which motivates further investment in the technology. Although no plants have yet been constructed in Germany there are several currently being negotiated (Aichernig, 2007; Vitek and Sommer, 2008).

Biomass integrated gasifier combined cycle, BIGCC and co-fire

The next step up in complexity is the Biomass Integrated Gasifier Combined Cycle (BIGCC) for combined heat and power production. The benefit of the combined cycle over a gas engine is that larger plants can be constructed with even higher electrical efficiency.

Several attempts were made to demonstrate the technology between 1991 and 2003, but they have all more or less failed (see Table 3.3.4). The most successful attempt was in Värnamo, Sweden, where a fully integrated BIGCC was demonstrated and was operational between 1993 and 1999 for a total of 8,500 hours based on various biomass feed-stocks. The plant was operated by Sydkraft (now owned by E.ON) with pressurised CFB technology from Foster Wheeler. The demonstration was completed in 1999 and the plant was then decommissioned.

Table 3.3.4: Biomass Integrated Gasification Combined Cycle for combined heat and power production.

Located in		**Supplier**	**Commissioned**	**MW_{th}**
Arbre, Yorkshire	United Kingdom	TPS	2003	30
Värnamo	Sweden	Foster Wheeler	1993	18
Tampere	Finland	IGT/Carbona	1991	20
Hawaii	United States	Renugas	1994	20

With a pressurised gasification reactor a BIGCC plant could, in principle, have a capacity of several hundred MW_{th}. The average size of the 23 currently operating coal-based IGCC is 440MW_{th}, and they have an electrical efficiency in the range of 38 to 43 percent (GASIF, 2007; Higman and van der Burgt, 2008). For biomass, plant size would be limited by the amount of available biomass and the size of the district heating (DH) systems. There are few DH systems capable of receiving hundreds of megawatts of heat.

Further technology development is required to commercialise the application, particularly with regard to turbine designs. Gas turbines with high efficiency and low NO_x emissions are developed either for coal-based syngas or natural gas. The biomass-based product gas has a lower calorific value than coal-based syngas and entirely different gas properties than natural gas (which mainly contains methane). With some development efforts it would probably be possible to redesign the burners for coal-based syngas to be used with syngas from biomass (Horazak, 2007a). In addition, the turbines would have to operate at a lower inlet temperature and pressure, which would increase the investment cost and lower the operational efficiency of such a plant compared to a combined cycle running on natural gas or a coal-based IGCC (Rodrigues et al., 2003).

Co-firing has been proposed as a solution to these technical problems. One type of co-fire system has already been demonstrated on a commercial-scale by the plant operator Nuon in Buggenum, the Netherlands. In this plant, coal and biomass is mixed and fed into a standard Shell EF gasifier. The plant has a 600MW thermal input and is co-fired with up to 34 percent thermal input of biomass (Zwart, 2007). It is not included in Table 3.3.4 since it is based on conventional coal gasification technology without any modification and has thus been excluded from the study.

A second type of co-fire application is discussed in Rodrigues et al. (2003) and Marbe (2005), but has never been demonstrated. They argue that it is possible to mix 28-50 percent natural gas with biomass-based product gas in an NGCC (Natural Gas Combined Cycle) without any major changes in turbine design or significant losses in efficiency.

Industry representatives disagree, however, and argue that only three percent of product gas can be used without modifications (Nyström et al., 2007).[75] This co-fire application appears to be promising for extending the design space towards realising BIGCC. However, as long as there are no actors making serious attempt to develop the technology, it is difficult to assess what the "minor" modifications suggested by Rodrigues et al. (2003), Marbe (2005) and Horazak (2007a) may actually be comprised of.

Chemicals and Transportation Fuels

Since the establishment of the EU directive on renewable fuels (EC, 2003), there has been renewed industrial interest in producing chemicals and alternative fuels from biomass. Past experience of biomass gasification for synthesising various chemicals and transportation fuels is, however, quite limited. There have been a few entrepreneurial experiments on a laboratory- and pilot-scale, based on both low and high temperature gasification.

In terms of industrial experience, no dedicated systems for biomass gasification for the production of second-generation fuels have been made operational. However, some lessons could probably be drawn from two major projects based on high temperature gasification using standard coal technologies. The first is an ammonia plant in Oulo, Finland based on peat, and the other is in Germany (Schwarze Pumpe), where methanol and power was produced from household and industrial waste from fossil resources. The peat used in Oulo and the waste at Schwarze Pumpe should not be seen as a renewable resource such as biomass, but they share some of the problematic physical and chemical properties that also have to be addressed for biomass gasification.

[75] The standard NG burners are, however, dry low NOx burners that are exclusively designed for natural gas. The issue is that dry low NOx burners are pre-mix burners and the syngas from whatever source contains hydrogen. The danger is that hydrogen under these conditions could pre-ignite (auto-ignition), causing at best overheating and damage to the burner. Industry's reluctance is therefore understandable (Higman, 2010).

The plant in Oulo, Finland was converted from oil at the end of the second oil crisis, and operated based on peat for a total of 258 days before it was shut down when the oil price dropped again (Koljonen et al., 1993). The plant had a thermal capacity of 80MW_{th}, operated at 10 bars of pressure and was based on the High Temperature Winkler, which is a coal technology supplied by the German capital goods manufacturer and engineering firm Uhde (see Chapter VIII). Schwarze Pumpe (SVZ) has a long history of coal gasification in the DDR but was converted to a facility for methanol and power production based on a mixture of processed coal and waste in 1996.

The technology originally used at SVZ was the GSP gasifier developed at the former Deutscher Brennstoff Institut (German Combustion Institute), which now is owned by Siemens, as well as fixed bed coal gasifiers for production of town gas (see Chapter VI). In 2000, a coal gasification technology called British Gas Lurgi (BGL), now owned by Envirotherm, was also installed to handle solid waste and coal together with the existing fixed bed gasifiers. The GSP technology was modified for handling oil slurries, pastes, fuel mixtures from tar, and sewage sludge. All operations at Schwarze Pumpe have been shut down since 2008 due to poor economics of the operation (Knoef, 2005; Picard, 2008b).

There are currently at least nine major projects within the European Union attempting to realise both high and low temperature biomass gasification along the three technological trajectories described above. These projects and their alliances will be described in Section 3.4. They draw on previous experience with biomass gasification for less advanced applications such as for lime kilns, boilers and co-fire, as well as from lessons from the previous attempts to realise BIGCC and the limited experience from Oulo and SVZ.

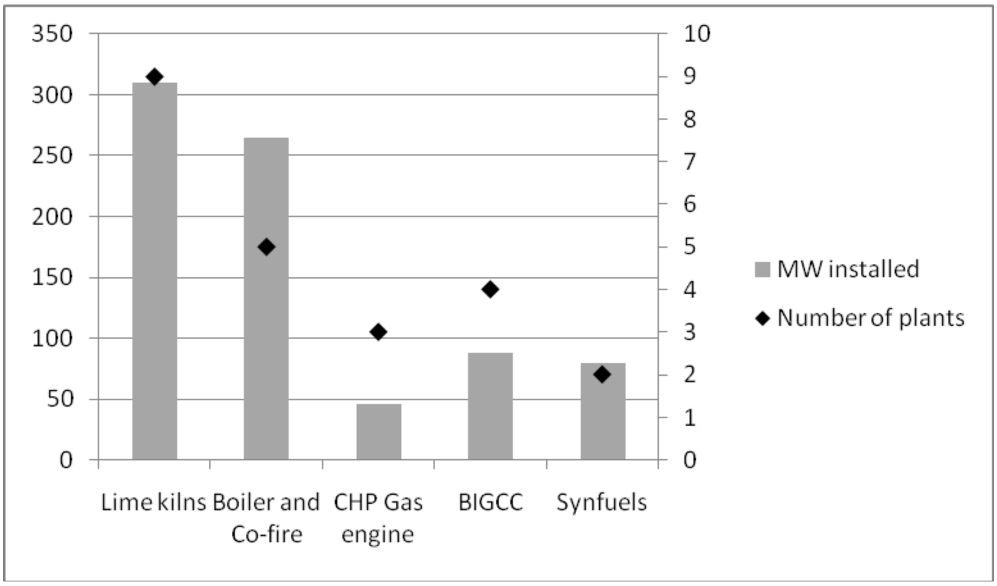

Figure 3.3.4: Accumulated experience in biomass gasification in terms of number of projects and MW installed capacity. Not all projects have been successful. Source: Tables 3.3.1-3.3.4.

In total, 24 biomass gasification plants have been constructed and supplied by ten major actors from four countries (Sweden, Finland, Germany and Austria) (see Figure 3.3.4 and Table 3.3.5). If future development draws on past experience, these ten actors would naturally be at the centre of any future development projects. However, their past experience will not be sufficient for developing future advanced applications for biomass gasification. In addition to existing knowledge, new advanced pre-treatment systems will have to be developed for high temperature gasification. The development of such pre-treatment systems may, in addition to feeding the gasifier, enable a global trade in low energy density biomass-based materials such as straw. For low temperature gasification, the challenge consists of developing efficient gas cleaning systems and adopting existing synthesis process (and eventually also gas turbines) to the low temperature biomass-derived synthesis gas. Hence, the catalyst developers would also have to take part in the development projects with their specialist competencies. There are potentially many suppliers of catalysts for methanol and DME synthesis who could take part in such a development, while there are only two suppliers of catalysts with industrial experience in FT synthesis (Sasol and Shell) (GASIF, 2007).

Table 3.3.5: Firms with some to extensive experience in biomass gasification, installed MW and number of projects. Source: Tables 3.3.1-3.3.4.

Experienced firms	Plants	MW
Foster Wheeler	10	321
Lurgi	4	212
TPS	2	60
Carbona	2	48
Uhde	1	80
Metso	1	30
Ortner	1	10
Repotec	1	8
Siemens	1	-
Envirotherm	1	-
Total	**24**	**769**

Hence, even if biomass gasification can draw upon the existing and fossil-based design space, there remain great technical challenges to realising more advanced applications. In order to successfully do so, new knowledge must be developed and combined with existing knowledge on fully integrated systems. The following section will outline the strategic alliances that have been formed to overcome this challenge along the three technological trajectories outlined.

3.4 Biomass gasification alliances in Europe and competing alternatives

This part is divided into three sections. The first section outlines the main projects and alliances for realising biomass gasification in Europe. Each project will be presented with a brief overview of which trajectory they have chosen, the alliance of organisations involved in its development, which development stage the project is at, and its demand for capital resources during the construction of the first pilot, demonstration and semi-commercial plants. The following two sections will outline the main arguments for the desirability of realising a market for second-generation fuels.

3.4.1 Major projects and alliances

The development of second-generation fuels and other chemicals is manifested through the construction of various demonstration plants. These projects are pursued by various types of organisations acting in different alliances.

These alliances include capital goods suppliers and catalyst developers for the coal and petro chemical-industry, pulp and paper firms, energy utilities, and equipment manufacturers from the transport sector. In addition, we find actors such as integrated gas and electrical utilities, refineries and fuel distributors, but also firms from the agricultural and forestry industries that handle large quantities of feed-stock. For some of these actors, the technology may be integrated into its existing operations, such as in the case of pulp and paper mills. These possibilities also exist for refineries, first-generation biofuels production facilities, and in district heating networks. In addition, the various alliances also include universities and institutes.

These alliances each focus on one of the three trajectories outlined in the previous section (EF, FB or FICFB) and a set of pilot, demonstration and semi-commercial plants have been built to advance the technology towards commercialisation for various applications, all of which can be classified as second-generation fuels. Nine of these alliances are found in Figure 3.4.1, and they will now be briefly described.

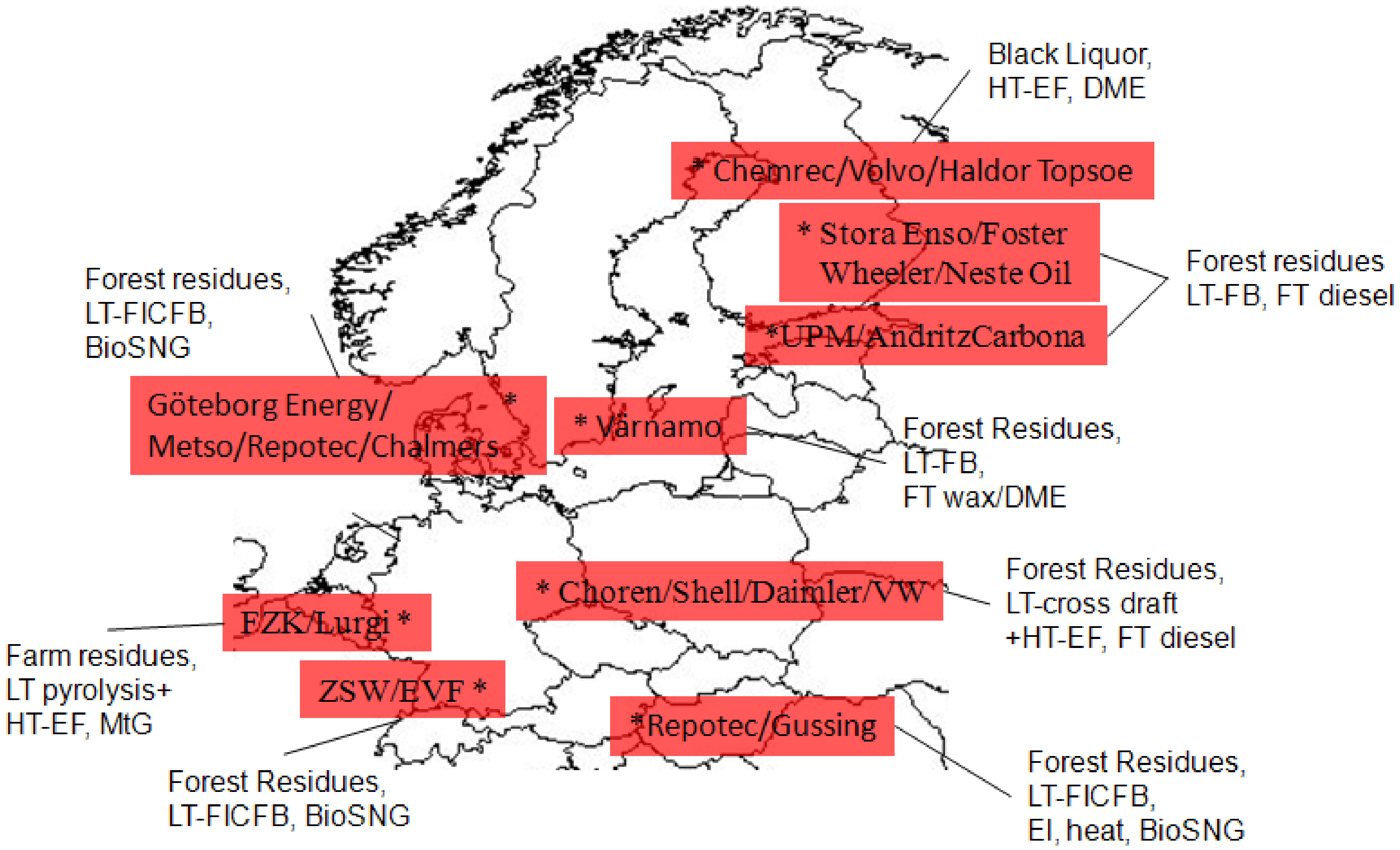

Figure 3.4.1: Major alliances for the production of second-generation fuels in Europe. Not all partners in the alliances are mentioned in the figure.

Figure 3.4.2: From the upper left-hand corner: The BioDME processing unit of Chemrec's demonstration plant in Piteå and a close-up of black liquor (Photo: Chemrec); the tower of FZK bioliq pilot plant in Karlsruhe (Photo: FZK); Choren's demonstration plant in Freiberg and a close-up of one of its biomass pre-treatment units (Photo: Choren).

Figure 3.4.3 From the upper left-hand corner: A close-up on Chalmer's FICFB gasifier (Photo: Henrik Thunman); a close-up of the pilot-scale gasification unit at VTT (Photo: VTT); the BIGCC demonstration plant in Värnamo (Photo: VVBGC); the commercially operating FICFB plant and demonstration facility in Güssing (Photo: Biomasse Kraftwerk Güssing).

In Austria (see Chapter V), the Technical University of Vienna and the engineering firm Repotec[76] developed the FICFB technology at the Güssing plant with, foremost, Conzepte Technik Umwelt (CTU) and the Paul Scherrer Institute from Switzerland[77] for the poly-generation of BioSNG, electricity and heat. The demonstration plant in Güssing is an $8MW_{th}$ gasification plant, in which 1MW gas is converted to BioSNG. The plant has been in operation since 2002 for heat and electricity, and the synthesis unit started to produce BioSNG in autumn 2009. The cost of constructing the facility was approximately €10 million, not including the synthesis plant (Hofbauer, 2007). The Austrian-Swiss alliance is currently seeking partnerships with capital goods suppliers for the construction of semi-commercial and commercial-scale plants in Europe (Hellsmark and Jacobsson, 2009). The technology is also being further developed in both Germany and Sweden. Since economies of scale for SNG production can be reached even in a relatively small plant, a typical future plant has been set at $100MW_{th}$. The investment cost for such a plant is approximately €150 million. The cost of BioSNG has been estimated to be approximately €0.7 per litre diesel equivalent (l_{de}) (see Table 3.4.1) (Thunman et al., 2008).

In Germany (see Chapter VI) two alliances have been formed with actors in the chemical, oil, coal and automotive industries, and a third is based on the FICFB technology developed in Austria. The first alliance was initiated by Choren, which is a start-up company from Freiberg. It has been developing the GSP gasifier for biomass gasification since the early-1990s and has formed an alliance with Daimler, Volkswagen and Shell for the construction of a fully integrated BtL demonstration facility, including FT synthesis technology supplied by Shell. If the plant can be made operational it will have an annual production capacity of 15,000 tonnes of fuel. The construction cost of the plant was over €100 million and it was inaugurated in April 2008. As of November 2009, the plant was not in operation and Shell had decided to sell its shares to the remaining shareholders in the company (Choren, 2009). When the demonstration is validated, Choren plans to move on to construct a commercial-scale demonstration facility with a production capacity of 200,000 tonnes of FT diesel. The

[76] Repotec is a spin-off company from the capital goods supplier Austrian Energy & Environment.
[77] Many other partners have been involved in the technology development, but it appears as if it is the commercial actors Repotec and CTU who will appropriate on the technology development.

estimated cost for such a plant is €800 million and the cost of the fuel will be in the range of €0.8-1.2/l_{de} (see Tables 3.4.1) (Seyfried, 2008b).

Table 3.4.1 Estimates of cost and time plan for the major development projects.

	Pilot		**Demo**			**Pre-Commercial Demo**			**Commercial demo**			**Cost**
	Year	*Cost (M€)*	*Year*	*Size*	*Cost (M€)*	*Year*	*Size*	*Cost (M€)*	*Year*	*Size*	*Cost (M€)*	€/l_{de}
TU-Vienna/Repotec	1995		2002	8+1MW	10	2013	160GWh	75	2015<	0.07Mtoe	150	0,7
Chalmers/Metso	2008	1.1	2008	6MW	1.1				2015<	0.07Mtoe	150	0,7
ZSW/EVF	2002	2.4	2010	10MW	18	2013<	10MW		2015<	0.07Mtoe	150	0,7
Chemrec	2005	7	2010	5MW/1.5kt	28	2012/13	0.1Mtoe	300	2015<	0.2Mtoe	400	0,5
Värnamo				18MW	45				2015<	0.2Mtoe	400	0,7
Carbona/UPM	2005	10				2011/12	0.2Mtoe	400	2015<	0.2Mtoe	500	0,5
FW/SE/Nesté			2009	12/5MW	40	2011/12	0.1Mtoe	400	2015<	0.2Mtoe	500	0,5
Choren	1998	NA	2008	45MW/15kt	100				2015<	0.2Mtoe	800	0,85
FZK/Lurgi	2005		2008	5MW	4	2011	5MW	70	2015<	0.2Mtoe	900	1
Total					***245***			***1245***		***1.41Mtoe***	***3950***	

Sources: Representatives from the different projects, as well as (Atrax Energi, 2002; Zwart et al., 2006a; Zwart et al., 2006b; Leible et al., 2007; Zwart, 2007; McKeough and Kurkela, 2008; RENEW, 2008; Thunman et al., 2008).[78]

The research institute Forschungszentrum Karlsruhe (FZK) has been the principal actor in the second alliance, in which they are attempting to develop a distributed solution for the gasification of agricultural residues. The idea is for the residues to be collected and turned into a slurry through fast pyrolysis, which is then transported from multiple locations to a single site for large-scale gasification with a high temperature EF reactor similar to the GSP marketed by Siemens and Choren. The demonstration of the technology is being pursued in collaboration with Lurgi, Volkswagen and Südchemie, but in the end Lurgi will be the sole owner of the complete process. The goal is to produce methanol that can then be turned into diesel, gasoline and other chemical products. In this project, the complete chain will be demonstrated separately and not in an integrated facility.

The demonstration facility for slurry production was inaugurated in 2008, and the advocates of the project hope to demonstrate the remaining steps before 2012, at a cost of approximately €60-80 million.[79] The cost of producing FT diesel from a very large commercial-scale facility with a capacity of 1.16 million tonnes has been estimated at approximately €1.0/l_{de} (Leible et al., 2007). Large plants are attractive since FT synthesis

[78] The intentions and time frames of the representatives of the different projects change quite frequently and the figures in Table 11.1 are often updated.
[79] This is the author's estimate.

benefits greatly from economies of scale. The production cost could eventually be decreased to approximately €0.55/l_{de} if plants in the range of 8GW_{th} are built (Zwart et al., 2006b; Zwart, 2007). On the other hand, if plants of the size of the Choren technology would be built (0.2 million tonnes), production cost would be as high as €1.8/l_{de} (RENEW, 2008). This type of plant is a possible intermediate step before the large-scale plants can be constructed, and through integration with, for example, the production of first-generation fuels, the production cost of the fuel could be reduced (Zwiefelhofer, 2007; Berger, 2008). The investment cost of a similar but smaller plant would still be around €900 million (RENEW, 2008), but a good estimate of the production cost of the fuel has not been made official. It would, however, be less than 1.8€/l_{de} but more than €0.5/l_{de} previously mentioned. Hence, even if not verified in the literature, a production cost of €1/l_{de} is used as a reference in Table 3.4.1.

The Repotec/Güssing FICFB technology has served as the basis for a third German alliance. The ZSW institute in Baden-Württemberg is seeking to further develop the technology for BioSNG production and has formed an alliance with a consortium consisting of more than 10 actors. They began elaborating with CO_2-absorbing bed materials for increasing the yield of hydrogen in the product gas. The attempts were carried out at the Güssing facility and received funding of approximately €2.4 million through the EU projects "AER-Gas I" and "AER-Gas II". In the next phase, ZSW and their allies will build a commercial-scale research and development facility for electricity production in the town of Göppingen. Through the EEG Act, which guarantees a fixed price for the electricity that is produced, the plant will carry its own operating costs and become a research facility for developing the process of BioSNG synthesis.

In Sweden (see Chapter VII) there are currently three alliances for realising biomass gasification for the production of transport fuels and chemicals. The first centres on FB gasification for the production of synthetic fuels based on the former BIGCC plant in Värnamo. The cost of reconstructing the 18MW_{th} facility has been estimated as approximately €45-50 million; reconstruction has not yet taken place and the project is currently on hold. The cost of constructing a commercial-scale facility integrated into a district heating network and having an annual production capacity of 0.2 tonnes of DME has been estimated as approximately €400 million. The production cost of the fuel from such a plant has been estimated to be in the range of €0.49-0.55/l_{de} (Atrax Energi, 2002) or €0.7-1.0/l_{de} (see Table 3.4.1) (Thunman et al., 2008).

The second alliance in Sweden was initiated by Chemrec, which has developed the black liquor gasification technology. The alliance aspires to produce DME using the black liquor from chemical pulp mills. A pilot facility for black liquor gasification was inaugurated in 2005, costing €7 million to construct; this is currently being rebuilt for €28 million as a demonstration facility for a continuous and annual production of 1,500 tonnes of DME. Inauguration of the facility is being planned for 2010 and will cover the fuel demand for a small test fleet of DME vehicles supplied by Volvo. Preem, Total, Delphi and other actors are also taking part in the project to develop the entire value chain—from black liquor to the use of DME vehicles in commercial traffic. The next step has already been initiated for the construction of a first semi-commercial-scale demonstration facility in Örnsköldsvik, Sweden. Chemrec, together with the pulp and paper mill Domsjö Fabriker, have been granted €50 million from the Swedish Energy Agency for the construction of a pre-commercial demonstration plant of approximately 100,000 tonnes annually at their mill site. The cost of the plant construction has been estimated as approximately €300 million (Domsjö, 2009). The cost of a commercial-scale plant in the range of about 200,000 tonnes of annual production has been estimated as roughly €400 million, when integrated into an existing chemical pulp and paper mill. Depending on the price and supply of raw material, the cost of liquids would be in the range of €0.5-0.7/l_{de} (see Tables 3.4.1 and 3.4.4) (McKeough and Kurkela, 2008; Seyfried, 2008b).

Biomass gasification is planned to be demonstrated in a third Swedish project, in which the local utility Göteborg Energy has teamed-up with the Austrian-Swiss alliance of Repotec, CTU and the Finnish capital goods supplier Metso Power for building the first semi-commercial 20 MW BioSNG plant. The construction cost of the plant will be approximately €75 million and the Swedish Energy Agency has decided to support the project with €22 million (Energimyndigheten, 2009c). The pre-commercial demonstration may be completed by

2013. In addition, Metso power and Göteborg Energy are involved in developing a new design of the FICFB technology, developed in Gussing, based on proposals by researchers at Chalmers University of Technology in Göteborg, Sweden. The new design enables most existing biomass CFB boilers to be retrofitted and turned into FCIFB units for, as an example, BioSNG production. A 6 MW pilot plant has been constructed at Chalmers for approximately €1.1 million. The technology will be ready to scale up with synthesis technology provided by CTU (see Table 3.4.1).

The capital goods suppliers in Finland (see Chapter VIII) significantly strengthened their ability to produce boilers and equipment for the pulp and paper industry over the past three decades. It is a process that is still ongoing with the recent entry of the Austrian machinery producer Andritz into that cluster. On the basis of a successful capital goods track record and a large pulp and paper industry, two competing strategic alliances have emerged. Both alliances develop fluidised bed gasification of forest residues for the production of FT liquids integrated into the infrastructure of the pulp and paper mills. The first alliance consists of Stora Enso (pulp and paper) and Néste oil, which have formed a joint venture; they are pursuing technology development together with Foster Wheeler (capital goods) and the Finnish research institute VTT. Together with the Finnish government, Stora Enso and Néste oil have invested more than €40 million to demonstrate the production of an ultra clean gas in an oxygen-blown, pressurised 12MW_{th} lime kiln gasifier, in which 5MW of the gas will be sufficiently cleaned for FT synthesis. The demonstration facility was inaugurated in 2009 (see Table 3.4.1).

The second Finnish alliance is composed of UPM (pulp and paper) and Andritz/Carbona (capital goods), in collaboration with the Chicago-based Gas Technology Institute (GTI). Chicago is also where all the technology development has occurred since 2005. Their development is based on a 6MW oxygen-blown, pressurised BFB reactor and a gas cleaning system developed by GTI and Carbona. So far, UPM has funded all the development at a cost of approximately €10 million, and have declared that they are willing to take the lead in an investment for a full-scale demonstration plant after all tests in the Chicago pilot plant have been completed (see Table 3.4.1).

FT production is currently not included in any of the demonstration projects in Finland. Nor is it clear which actors will supply the necessary FT technology in the future. Both alliances aim at integrating the technology in existing pulp and paper mills where there are sufficient residues and hope to have a first commercial demonstration of 100-200 tonnes of liquids ready sometime before 2015. Depending on the price and supply of raw material, the cost of liquids would be in the range of €0.5-0.7/l_{de} (see Table 3.4.1) (McKeough and Kurkela, 2008).

Except for Värnamo, all of these nine projects are sufficiently funded to complete the demonstration phase, which is estimated to cost approximately €250 million by 2010 (see Table 3.4.1). Additional funding will most likely be necessary as the projects run into unforeseen technical difficulties. Even if demonstration has already begun or is expected to begin during 2010, given the complexity of the task and various uncertainties, most alliances cannot be expected to start pre-commercial demonstration before 2012-2013.

The cost of pre-commercial demonstration of five of the above-mentioned nine projects will be no less than €1,300 million. This figure can be compared with what has been considered a significant funding scheme in Sweden: a budget of more than €80 million for realising these type of projects (Energimyndigheten, 2008). It is also from this scheme that Göteborg Energy and Chemrec have managed to secure a total of €72 million for pre-commercial demonstration (Energimyndigheten, 2009c).

Hence, if pre-commercial demonstration projects are technically successful, there is a slight chance that the construction of the first commercial-scale plants can start sometime after 2015. Supposing that nine such plants are constructed by 2020, it would involve an investment of about €4 billion and result in the production of approximately 1.41 Mtoe of fuel—equivalent to 5 percent of the 10 percent directive for 2020 (0.5 percent of the total fuel market, if consumption is kept constant at 300Mtoe annually).

The nine different projects propose three main alternative fuels (FT diesel, DME and SNG) and three different technology trajectories to achieve them. These alternatives are simultaneously complementary and in direct competition with each other and other alternative fuels. The two following sections will outline the main arguments in terms of the desirability of realising a market for second-generation transportation fuels based on biomass gasification. First, the focus will be on the main substitutes and the main arguments for and against the different options.[80] Second, the focus will shift to the various costs, and the potential social and economic benefits of realising a market for second-generation biofuels.

3.4.2 Alternative fuels competing to substitute oil

The main fuel alternatives from biomass gasification pursued by the nine alliances are Fischer Troops diesel, synthetic natural gas and dimethylether. The advocates for FT diesel argue that it is the most environmentally friendly alternative, which can be blended directly with ordinary diesel at any quantity and is, therefore, a preferred choice. In addition, they argue that diesel engines are the most energy-efficient engines available and that there is an increasing shortage of diesel on the world market. As diesel and gasoline are produced at a fixed ratio at refineries, it would make more sense to produce a diesel substitute from biomass than a gasoline substitute (Keppeler, 2007; Kaikkonen, 2008; Picard, 2008a; Seyfried, 2008a).

The advocates of DME and SNG argue that the construction of new infrastructure is a comparatively minor cost since there are also costs associated with maintaining existing infrastructure. The construction of new infrastructure can, according to the advocates, be attractive since DME and SNG can be converted from biomass at a higher level of energy efficiency than FT diesel. In addition, with further engine development, both DME and SNG can be used as a diesel fuel with the same high level of engine efficiency as FT diesel (Danielsson, 2008; Röj, 2009).

There is a conflict between SNG and DME. The advocates of SNG argue that it is a flexible fuel that also can be used in many industrial processes, and that there already exists infrastructure for natural gas on which one can continue to build (Gunnarsson, 2009; Sjöström, 2009). The advocates of DME, on the other hand, argue that the DME catalysts are commercially available and widely used. Moreover, production is seen as flexible since it can

[80] Excluded from the analysis are potential energy savings, lifestyle changes, increased use of public transport or rapid increase of electrical vehicles, as well as other more elaborative fuel alternatives such as using algae for fuel production.

easily be shifted between methanol and DME and the end products have many other industrial uses besides transportation fuel (Gebart, 2008; Rudberg, 2008).

Second-generation fuels from biomass gasification compete with other alternative fuels based on both fossil and renewable resources. This competition will be discussed here with regards to their potential to replace conventional oil, reduce CO_2 emissions, and the cost of producing second-generation fuels. The replacement potential of the second-generation fuels was illustrated in Chapter I, which concluded that the uncertainty concerning the substitution potential is great[81] (6-56 percent) and that only a limited share of the current fuel market can be substituted with second-generation fuels from biomass.

The substitution potential is even less for first-generation biofuels, since their well-to-wheel energy efficiency is considerably lower than that of gasification (see Figure 3.4.4). In addition, they continue to be controversial since they compete directly with food production. Depending on the production method, the CO_2 reduction potential varies extensively—from being almost on par with the gasification of biomass to even worse than oil-based fuels (see Figure 3.4.4).[82]

[81] Depending on the well-to-wheel efficiency and the allocation of biomass for fuel production.

[82] Please note that SNG is not included in the figure, but that it is, however, on par with DME. The only fossil alternatives mentioned in the figure are conventional diesel and diesel, as well as gas-to-liquids (GtL) and coal-to-liquids (CtL). The remaining alternatives outlined in 3.4.5 have an environmental performance somewhere between conventional diesel and coal-based diesel. Their exact environmental performance is not of interest to this study, only that they are worse than the existing alternatives and potentially abundant in supply.

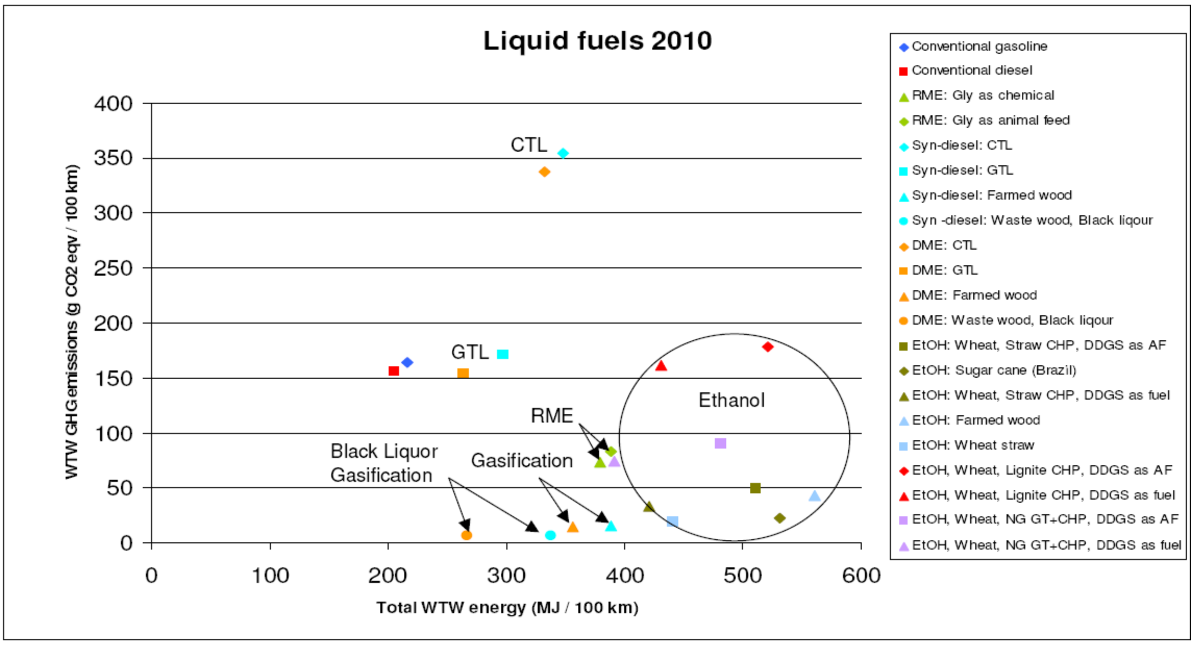

Figure 3.4.4: Total WTW GHG emissions and the total WTW energy for common alternative fuels (IES JRC, 2007).

The substitution potential of the fossil-based alternatives is considerably higher than the renewable alternatives, and they can, in general, be produced at a lower cost. Based on current global liquids consumption of approximately 31 billion barrels per year (BP, 2009), the remaining known fossil resources (8,000 billion barrels) would last for at least the next 258 years. Nearly 1.1 trillion barrels have already been produced at a cost of up to $30 per barrel (in 2008 dollars) (see Figure 3.4.5). The production cost of these fossil alternatives varies between $10-120 per barrel (bbl), while second-generation fuels can be produced for approximately $80 to $165/bbl (see Table 3.4.2). On the other hand, CO_2 emissions from the fossil alternatives are up 2.3 times higher than from conventional fossil fuels (IES JRC, 2007). The environmental consequences of utilising this potential would, therefore, be devastating.[83]

[83] The future legitimacy of fossil gasification will most likely depend on how well the advocates of coal gasification manage to integrate CCS technology into their future projects. However, CCS technology increases energy consumption and increases the rate of coal depletion (Holt, 2007).

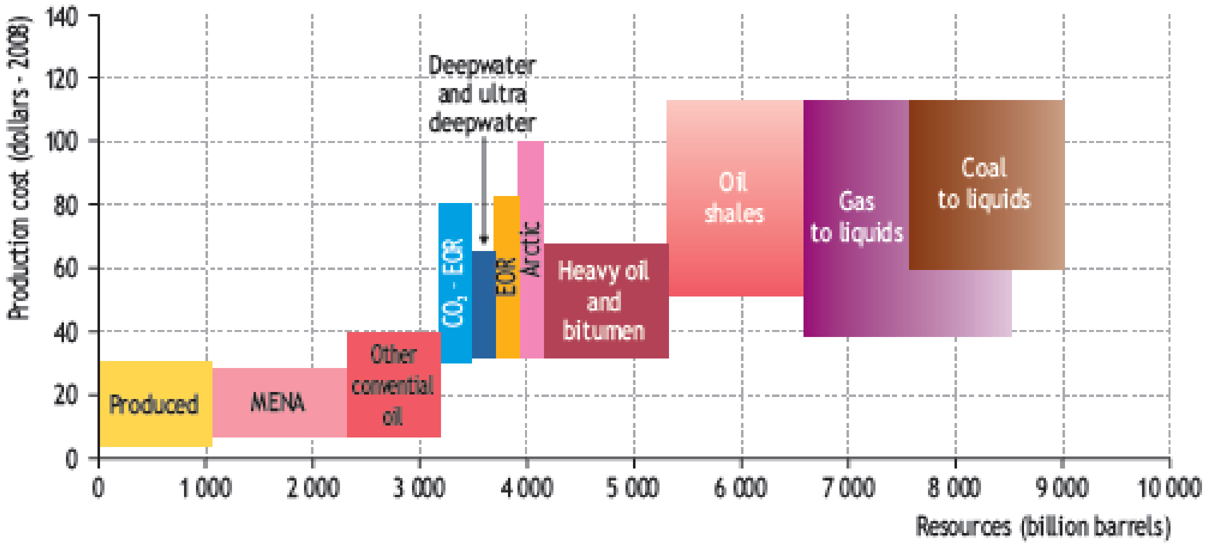

Figure 3.4.5: The long-term supply of liquids from conventional and unconventional resources. In the figure, "Produced" refers to the amount of oil already recovered and used. Source: IEA (2008, p. 218).[84]

If climate change is a prioritised goal and energy security is added into the equation, renewable alternative fuels will have to be developed to limit the amount of fossil-based alternative fuels made available on the market.

In sum, the gasification of biomass appears to be an attractive and desirable option. It can potentially be produced from domestic resources in relatively large quantities, and substitute 6-56 percent of the current demand for oil in the long run while significantly reducing CO_2 emissions. The actual substitution potential depends on the choices made; however, none of the upcoming renewable alternatives can be expected to substitute all of the oil currently used.

The following section outlines the desirability of biomass gasification in terms of the cost of realising it, as well as possible social and economic benefits beyond CO_2 reduction.

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[84] Note: The curve shows the availability of oil resources as a function of the estimated production cost. Cost associated with CO_2 emissions is not included. There is also a significant uncertainty on oil shale production cost as technology is not yet commercial. MENA refers to the Middle East and North Africa. The shading and overlapping of the gas-to-liquids and coal-to-liquids segments indicate the range of uncertainty surrounding the size of these resources, with 2.4 trillion shown as a best estimate of the likely potential for the two combined" (IEA, 2008, p.218).

3.4.3 The cost, desirability and risks of realising a market

In the introductory chapter, the potential of biomass was assessed and it was concluded that it would be realistic, from a European resource perspective, to realise a 25 percent market (or 77Mtoe) share based on current fuel consumption. To realise this potential, it must be created in competition with other uses of biomass and by choosing the conversion technologies with the highest possible well-to-wheel efficiency. Even if the potential is highly uncertain, it is used as a point of departure for investigating the cost and desirability of realising a market for second-generation fuels.

Based on the figures in Table 3.4.1, the investment cost in a commercial plant with a production capacity of 1Mtoe of fuels is in the range of €2-4 billion.[85] The total investment cost includes all equipment necessary for biomass treatment, gasification and fuel synthesis. To realise a production infrastructure (not including distribution and consumption) with a capacity of producing 77Mtoe of renewable fuels, it would require a total investment in the range of €150-300 billion[86] in the years to come.

The long-term employment effects in terms of plant operation, biomass production and collection would be significant if such a market would be realised. Based on data supplied by the interviewees, a plant with a production capacity of 0.2Mtoe of fuel would employ in the range of 600-850 people (Jokela, 2008; Rudloff, 2008a). To realise an annual European market of 77Mtoe, an equivalent of 385 plants would have to be built and be in full operation. The employment effect of growing and collecting biomass, as well as operating these plants, would, therefore, be in the range of 230,000-330,000 people.[87] The short-term employment effects in the sector associated with building the plants and the potential of an export market would, of course, also be considerable. However, these figures are not quantified here.

[85] The estimates for the Chemrec/Värnamo/Carbona/FW and Choren technologies in table 3.4.1 indicate that the investment cost of building a plant with the production capacity of 0.2Mtoe equals approximately €400-800 MEUR. Therefore, the specific investment cost in plants with a production capacity of 1Mtoe of fuel equals €2-4 billion.

[86] 77*2=154 and 77*4=308

[87] 77Mtoe divided by an average plant size of 0.2Mtoe equals 385 production facilities. If each facility employ 600-850 people, it creates 231,000 – 327,250 jobs.

If the EU would realise such a market based on domestically grown biomass, 77Mtoe of oil imports would be avoided.[88] Depending on future oil prices, these avoided costs could be substantial. The IEA (2009) World Energy Outlook refers to two main scenarios, one in which the nominal price of oil will reach \$150/bbl by 2030 and another in which it will reach \$190/bbl. If a 25 percent market (77Mtoe) would be realised by 2030, the EU would avoid oil imports in the range of €60-80 billion (\$80-100 billion) annually.[89] Hence, in addition to CO_2 reductions, a 25 percent share of second-generation fuels from biomass would generate substantial benefits.

Uncertainty about the future price of oil is, however, practically guaranteed. From having been relatively stable around an historic average of \$38/bbl (EIA, 2009)—except for temporary peaks during the oil crises in 1973 and 1978—the price of oil has recently increased rapidly. In the last week of January 2007, it went above \$50/bbl and continued to increase until it peaked at \$137/bbl during the first week of July 2008. Since then, it has dropped to \$36/bbl during the last week of December 2008 only to increase again. During the first two months of 2010, it fluctuated around \$70-80/bbl. These fluctuations in price levels can also be seen in the future projections of oil prices. In their 2007 reference scenario, the IEA predicted that the price of oil in 2030 would be \$62/bbl (IEA, 2007). And only two years later, in their 2009 edition, the price of oil was expected to be \$150-190/bbl by 2030 (IEA, 2009).

Bearing this price volatility in mind, Table 3.4.2 summarises the estimated production cost of second-generation transportation fuels from the various demonstration projects. The demonstration facilities that plan to integrate fuel production in the pulp and paper industry are found in the lower end of the range. They could possibly be competitive at an oil price of approximately \$80/bbl, while the most expensive solution, provided by FZK/Lurgi, would only be competitive at an oil price of about \$165/bbl (see column 2 in Table 3.4.2).

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[88] It has previously been mentioned by the European Commission that importing oil has very limited employment effect compared to utilising domestically grown biomass for substituting oil (EC, 2008).

[89] 1Mtoe=7.3Mbbl, 77Mtoe=563Mbbl. At a future oil price of \$190/bbl, the import savings would be \$107 billion. At \$150/bbl it would be \$84 billion. Hence, €60-80 billion at an exchange rate of 1 USD = 0.73 EUR (2010-10-04)

However, if the cost of CO_2 emissions is set and the renewable alternatives are excluded from such costs, their competitiveness would naturally increase. Since there is no general EU framework associating CO_2 emissions from the transport sector with a cost, the question is: what would a reasonable price for future CO_2 emissions from the transport sector be? If the cost of emitting CO_2 would be set in the range of the Swedish CO_2 fuel tax (equivalent to approximately $50/bbl of gasoline),[90] the pulp and paper solution would be competitive at about $32/bbl, while the FZK/Lurgi solution would be competitive at about $114/bbl (see column 3 in Table 3.4.2).[91]

The Swedish CO_2 fuel tax is, however, relatively high compared to the price of CO_2 emissions set at the European Climate Exchange (ECX) for sectors included in the European CO_2 emissions trading scheme (currently not including the transportation sector). In the period between January 2008 and December 2009, the average price was €19.6/ton CO_2 (ECX, 2010). Assuming that the combustion of 1 barrel (159 litres) of diesel emits 0.414 tonnes of CO_2, it would cost €8.11/bbl or approximately $10/bbl depending on the exchange rate. If the cost of emitting CO_2 was equivalent to $10/bbl, second-generation fuels would be competitive if the price of oil was higher than $72-155/bbl, depending on the production method (see column 4 in Table 3.4.2).

From the perspective of an investor in a future commercial-scale BtL plant, it should by now be quite obvious that such an investment is associated with high risk. First, a large amount of money is put at risk, about €400-800 million depending on the type of plant. Second, the competitiveness of the plant is completely dependent on an uncertain future with regard to the price of oil and the level of CO_2 rebates.

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[90] The price was set in Swedish krona per litre of gasoline. As of January 1, 2010, it was SEK 2.40/litre (Skatteverket, 2010).

[91] The price at which the different cases are competitive was calculated by multiplying the expected production price, litre per diesel equivalent with the number of litres in a barrel of oil (159 litres). Refinery losses, equaling 10 percent, which occurs when upgrading crude oil to diesel, has been deducted by multiplying the figure by 0.9. The conversion from Euro to Dollar has been based on the historic average exchange rate between 1998 and 2008 (1 EUR = 1.15 USD).

Table 3.4.2: The production cost of BtL and its competitiveness in relation to the price of oil when no, a high and a low CO_2 tax is included in the calculation.

Projects	(1) **€/l$_{de}$**	(2) **\$/bbl**	(3) **\$/bbl$_{High-CO2tax}$**	(4) **\$/bbl$_{Low-CO2tax}$**
TU-Vienna/Repotec	0,7	115	64	105
Chalmers/Metso	0,7	115	64	105
ZSW/EVF	0,7	115	64	105
Chemrec	0,5	82	32	72
Värnamo/Chrisgas	0,7	115	64	105
Carbona/UPM	0,5	82	32	72
FW/SE/Nesté	0,5	82	32	72
Choren	0,85	140	89	130
FZK/Lurgi	1	165	114	155

If sufficient incentives are provided and the risks to investors are absorbed by various EU governments or through a common legislative framework, there is a chance that a 25 percent (77Mtoe) market for second-generation fuels can be realised (see Chapter XI for an extended analysis). Absorbing this risk, however, may entail a significant cost depending on the future price of oil, the price of CO_2 emissions, and the average cost of producing BtL (see Figure 3.4.6).

The X-axis in Figure 3.4.6 represents the price of oil. At an historic oil price of $38/bbl, the cost of realising the market by providing sufficient incentives for investors would be nearly $70 billion annually,[92] if the average BtL cost is $165/bbl. At an oil price of $190/bbl, the annual savings would, however, be approximately $80 billion, if the average cost of producing BtL would be as low as $30/bbl.

92 This is considered to be high, since the EU budget for 2008 was €116.5 billion. If taken from the budget (which would be unrealistic) it would be the largest part in the budget. Agricultural subsidies in the EU budget for 2008 totaled €43 billion (EC, 2009b).

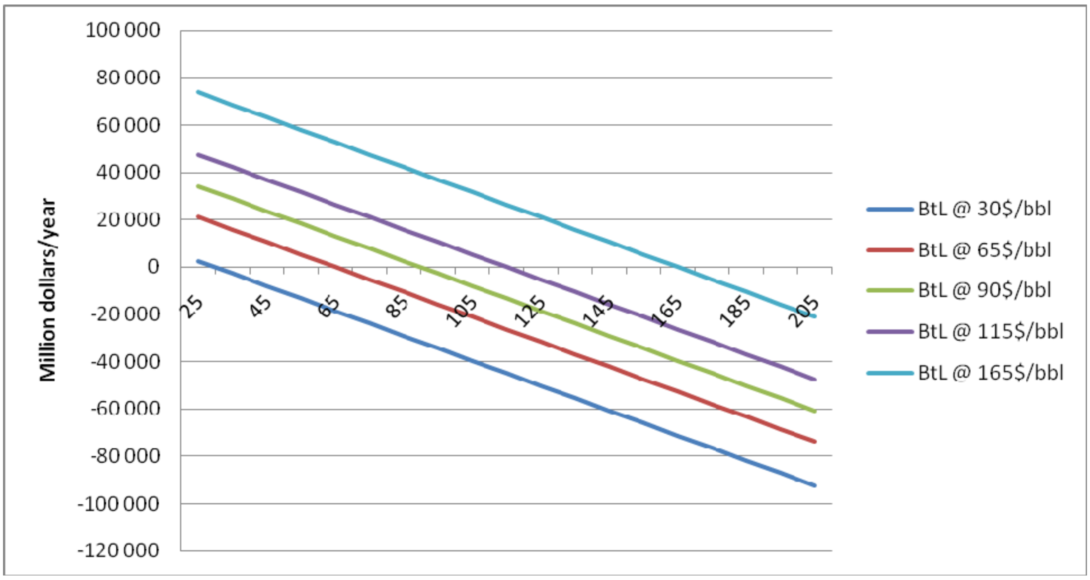

Figure 3.4.6: The cost of realising 25 percent BtL market at an average BtL production cost of $30-165/bbl at various oil prices.

In sum, without any mechanisms to absorb the risk for investors that are expected to make investments in the range of €150-300 billion, it is unlikely that a 77Mtoe BtL market will ever be realised. Yet, in addition to improving the security of supply, job security and reducing CO_2 emissions, the economic benefits for society in providing such incentives may outweigh the costs, if the oil price remains high and production costs of second-generation fuels can be kept down.

3.5 Summary

Over the past 200 years, the design space of pyrolysis and gasification has evolved through many different applications and where the capacity of making one has led to another (cf. Rosenberg (1976)). The technology has evolved from being used for lighting and cooking during the industrial revolution into a cornerstone of the modern chemical industry in the production of various chemicals, nitrogenous fertilisers, and FT liquids and power.

The preferred feed-stock throughout the history of gasification has been coal, although during the abundance of cheap oil such plants were also built. Since the 1970s, coal has once again increased in importance, and off-grid natural gas fields have been identified as a potential resource for increasing production and for securing the future supply of liquid transportation fuels. The use of coal for such purposes could potentially be devastating to the environment, as it emits 2.3 times more CO_2 than do conventional fuels.

Given increasing concern about climate change, interest in extending the design space of gasification to also include biomass, peat, black liquor and low-value waste resources has picked up. The first experiments with biomass since the Second World War were conducted as early as the 1970s. Since that time the field has evolved along three main trajectories. These include two low temperature routes: pressurised fluidised bed and atmospheric fast internal fluidised bed, both of which were offshoots from the existing knowledge base in fluidised bed combustion. The third trajectory is a high temperature route, which is an offshoot of existing reactor designs for coal and oil gasification based on the entrained flow reactor.

The various types of biomass are different from fossil fuels, both in their physical characteristics and chemical composition. To use it in any of the three routes for the purposes of producing transportation fuels requires major adaptations to and development of the processes. In general, the low temperature routes based on fluidised beds are relatively easy to feed with biomass, while the main problem lies in the downstream gas cleaning equipment and the catalysts for synthesising the gas. On the other hand, if the high temperature route is applied, the same downstream process used for fossil gasification can probably be used with only minor modifications. However, the physical characteristics of biomass make feeding troublesome and new methods for pre-treatment have to be developed. Hence, regardless of which route is chosen, there are further technical problems that need to be solved. Solving these problems involves adapting, developing and demonstrating the entire system from feed to fuel—not just the individual steps of the process.

In order to realise biomass gasification for the production of transportation fuels and other chemicals, an industry with the capacity to construct large-scale gasification systems has to emerge. The embryo for such an industry has been in development since the 1970s, experimenting with less advanced applications from low temperature gasification. The first experiments took place without gas cleaning, where the gas was substituted for oil in the lime kilns. It continued later with experiments on various boiler applications and in gas engines for CHP production, which required only modest gas cleaning. Attempts have also been made to develop the BIGCC application for CHP generation, but without much success. Based on previous experience from biomass gasification in combination with experience in fossil gasification, nine prominent alliances have been formed for realising the production of renewable transportation fuels and other chemicals based on the three routes outlined above.

These alliances offer solutions that complement each other and compete with each other in the realisation of a market for renewable transportation fuels. From a resource perspective, the potential has been assessed as somewhere between 6-56 percent. If a 25 percent market is realised, CO_2 emission would be reduced, energy security would be improved as imported oil to a value of €60-80 billion ($80-100 billion) would be substituted for. In addition, job security could be improved by generating economic activities that would not be otherwise possible. For example, approximately 230,000 to 330,000 jobs could be created in biomass cultivation, collection and fuel production, not to mention additional jobs in the capital goods industry for plant construction, both domestically and for export.

However, even if the production of second-generation fuels is a socially desirable process compared to the fossil alternatives and first-generation biofuels, it is more expensive. For realising a potential market of 25 percent over the longer term, investments in the range of €150-300 billion must be made. Without any further incentives, the risk to investors will be too large and the potential will not be realised. How such incentives may be constructed will be discussed in Chapter XI of the thesis.

Part II of the thesis will describe the history of biomass gasification leading up to the emergence of the nine projects mentioned above. It will also outline the main challenges for realising them from a national perspective (Austria, Germany, Sweden and Finland). Part III of the thesis will draw upon these chapters and analyse what will be necessary at a European level to realise an industry with the capacity to supply plants for the production of second-generation fuels on a commercial-scale.

Chapter IV
Method

"… economics is essentially a unique process in historic time."

(Schumpeter, 1954, p.12)

The purpose of this chapter is to describe the methods used for the TIS analysis conducted in this thesis. The chapter is divided into three sections. The first starts by outlining the basic virtues of performing a TIS analysis and what its possible contributions can be. The second section describes the case study methodology and delineates the field of study. The third section describes the evolution of the research process and the methods used for data collection and analysis.

4.1 The virtue of a TIS analysis of biomass gasification

The world we live in is a "non-ergodic" one, "… a world of continuous novel change" (North, 2005, p.16). In the long run, institutional, market, organisational, and technological uncertainties are almost complete in such a world. For these reasons, it is next to impossible for individual actors to be well-informed and be able to take sensible actions in developing new technologies today based on beliefs about the future decades from now.

Genuine uncertainty inhibits actions and provides weak incentives to develop and experiment with technical solutions with a high-potential over the long-term. Since the development of new knowledge fields and the creation of an industrial capacity for large-scale diffusion take decades, an important role of policy in the face of climate change is to reduce such uncertainties and thereby stimulate the emergence of new industries with potential solutions for addressing the emerging threat.

However, we also know that humans are rationally bounded and may act anyway. We learn and make decisions based on our individual contexts, rather than doing so free from previous constraints based on equally available and well-developed information. We also know that knowledge, institutions and other parts of the structure are cumulative, and that by analysing and understanding the structural context in which the actors are embedded, it becomes possible to understand how choices made in the past influence choices in the future (Rosenberg, 1976; Simon, 1979; North, 2005).

For research to matter to policymaking, context-specific analysis is pivotal as it givens an understanding of how and why different actors decide to learn and develop a new knowledge field, as well as which uncertainties have to be reduced in order for these actors to continue making choices that, in the long run, may progress the field towards commercialisation.

The value of this thesis is not in making predictions about the future. Rather, it is to provide a highly context-dependent analysis on what it takes for a range of actors, from both the public and private sectors within the European Union, to realise an emerging TIS with potential to contribute to abating climate change.

The virtue of such an analysis may be viewed as fundamentally different from what is expected from research originating at a technical university, which normally has a positivistic-oriented science base. With such an epistemological point of departure, the theoretical abstractions which are free from context-dependent assessments are held in highest esteem (Alvesson and Sköldberg, 1994; Flyvbjerg, 2001).

However, as many researchers have pointed out before, social systems are not the same as those governed by natural laws (cf. Giddens (1984b), Månson (2000)). The primary reason for this is that the main object of analysis in social science—the actor—is also a subject that makes choices based on his/her specific context, history and personal values (Rosenberg, 1976). Hence, in order to understand the agency of the actor one also has to focus on the context within which this actor operates. It is thus not possible to achieve a deep understanding of the emergence of an industry that is very much dependent on the decisions made by individual actors (see Chapter II), without also providing context-dependent observations and conclusions.

Flyvbjerg (2001, 2006) argues that social science is strongest where natural science is weakest and that it has its true virtue in addressing such highly context-dependent phenomena. This is not to say, however, that context independent and general theories are not possible, or not valuable, in social science. By addressing such phenomena, valuable questions can be answered where natural science methods are clearly limited. According to Flyvbjerg (2006), social science has a clear advantage in contributing by providing answers to at least the following questions:

a) Where are we going?
b) Is this development desirable?
c) What, if anything, should we do about it?
d) Who gains and who loses, and by which mechanisms of power?

Even though no single researcher can be expected to fully answer all of the above questions for any given purpose, one can at least make partial contributions. Furthermore, the perspective here is that a final and definitive answer cannot be given, but that one can contribute by providing a complementary or a better explanation than those provided in the past.

In this thesis, the first question is analysed by unfolding the recent history of biomass gasification, leading up to the nine most prominent gasification projects in Europe. This includes an analysis of which specific technological trajectories the different actors have embarked on, and which claims that are made with regard to their ability to provide renewable liquids for the future.

Since knowledge is cumulative (Dosi, 1982) and current development can be expected to follow the technological trajectories outlined in Chapter III, it is possible to provide a relatively credible answer to the question about the direction in which we are heading, at least in a technical sense. However, there remains a high risk of failure in both the individual projects studied and for the entire TIS. The question concerning direction is addressed in Chapter III, based on the technical evolution of the field and its relationship to fossil gasification and fluidised biomass combustion. In Chapters V-VIII, the specific evolution of the knowledge field in four different countries are outlined, and Chapter XI looks forward and analyses what it takes to realise the field on a large-scale by addressing the existing system weaknesses and uncertainties.

The second question posed by Flyvbjerg (2006) concerning the desirability of current development is from my point of view by far the most difficult one to make a contribution to. Being a student of the development of a specific technological field entrenches you in that field; the values and reasoning of actors in that field soon become your own and making any type of "objective" assessment concerning desirability becomes next to impossible. I have always believed that it would disqualify me from any discussions on the future desirability of second-generation fuels.

However, during the project it has become obvious that most studies claiming to make objective assessments concerning the desirability of various renewable alternatives are, more or less, entrenched in one technological regime over another. These studies play an important role in either legitimising the TIS or discrediting it. Such studies, therefore, take part in the reproduction of these belief and value systems over others (Bergek et al., 2008c). Since most assessments concerning desirability can be seen as more or less skewed, I see no good reasons for not contributing my own perspective on the desirability of the technology. An overview of the main arguments for supporting the formation of an industry with the capacity to realise the potential of biomass gasification was presented in Chapter I, as well as in the two final sections of Chapter III.

The fourth question, "Who gains and loses, and by which mechanisms of power?", addresses changes in the underlying power structure of, in this case, the given TIS. The question is explicitly addressed when analysing the nature, extent and limits to the transformative capacity of the system builders (RQ 2 and 3). With such an analysis, it becomes possible to understand what the actors are able to do given the existing institutional structure, but also what types of intentional and frictional resistance they encounter from, for example, incumbent actors when attempting to strengthen the TIS, and which type of weaknesses and uncertainties they are unable to address. Answering that type of question is necessary for being able to address the third of Flyvbjerg's four questions: "What, if anything, should we do about it?"

In this thesis, this corresponds to the fourth research question: "*Given these limits, which system weaknesses remain to be resolved by system builders and policymakers on different levels (national and EU)?"* Such policy lessons are presented for each case study country (Chapters V-VIII) in Part II, as well for the entire EU in Part III (Chapters IX-XII).

4.2 Case study methodology and defining the case

Case studies have been described as an appropriate method for studying contemporary phenomena (Yin, 2009), where context-dependent knowledge can be expected to be important (Flyvbjerg, 2001), and in areas where little theory has been developed (Eisenhardt, 1989).

The phenomenon of this thesis is clearly contemporary and the actors are likely to make context-dependent decisions that are important to understand for the given purpose. However, this is not a field where there is a lack of existing theory or where little has been developed. If this were the case, it may have called for an inductive, grounded theory, case study approach such as that outlined in Strauss (1987) and Miles and Huberman (1994). On the contrary, however, the field of evolutionary economics and industrial dynamics has—since the 1970s—been the main topic for many researchers, and the question of the industrialisation of new knowledge fields has been on the agenda of innovation systems research since the early-1990s.

Instead, a methodological approach based on "systematic combining" has been adopted to maximise use of existing theory. The methodology has been defined as a " … process where theoretical framework, empirical field work and case analysis evolve simultaneously … " (Dubois and Gadde, 2002, p. 554). With systematic combining, it is possible to depart from what has been described as "tight and pre-structured" theoretical framework such as the TIS framework (Miles and Huberman, 1994; Dubois and Gadde, 2002).[93] According to Dubois and Gadde (2002), the proposed methodology makes it is possible to "confront" existing theory with an empirical reality, continuously move back and forth between empirical

[93] Rather than a "loose and emergent" framework as described in Miles and Huberman (1994).

observations and the framework, and thereby expand the understanding of both the evolving framework and the empirical observations.[94]

One of the major challenges of case study research is defining the case—what the case is a case of—and deciding whether a single or multiple case study approach should be adopted (Yin, 2009). In this thesis, deciding on the case study is the same as deciding on the TIS and delineating the system. In Chapter II it was illustrated that the TIS should be delineated in terms of the scope and extent of the knowledge field, its relationships in terms of being part of or adjacent to one or several sectoral innovation systems (SSI), and in spatial terms as part of a one or several national and/or regional innovation systems (NSI, RSI) (Carlsson et al., 2002a; Carlsson et al., 2002b; Markard and Truffer, 2008).

In terms of the scope and extent of the knowledge field, the dynamic concept of "design space" was introduced to capture the constant evolution of the knowledge field (Carlsson et al., 2002a). The design space is, therefore, not fixed over time, but evolves as it is confronted with new problems, allowing new solutions to be developed. Hence, as an industry successfully experiments with a given design space and extends it into new areas, they also develop a capacity for new applications (Rosenberg, 1976). Chapters III and V-VIII therefore illustrate how the design space of biomass gasification has evolved along three main trajectories and how the industrial capacity to realise biomass gasification for various applications has evolved by moving back and forth between more and less advanced applications of the gas. The scope and extent of the knowledge field has thus been limited to the development of the design space along the three mentioned trajectories (see Figure 3.3.1 in Chapter III, and Figure 4.1 in this chapter).[95]

[94] By analogy with abduction, see Alvesson and Sköldberg (1994) for an overview of induction, deduction and abduction.
[95] While there are several other biomass-based technologies that evolved in parallel to the three dominating ones, they have been excluded from the analysis. Progress within these technologies would eventually also strengthen the capacity of the actors in the TIS to realise renewable fuels. For example, advancements in the cleaning systems for fixed bed systems could also benefit FB systems. Conventional large-scale coal technologies such as the Nuon plant in Buggenum, which uses biomass by mixing it with coal, are also excluded from the TIS. It is excluded since only relatively small volumes of biomass can be used without changing the design of the plant. If such a set-up would be used to produce synthetic liquids, it would also increase the CO_2 emissions considerably compared to conventional diesel and gasoline, even if mixed with biomass.

An overview of the delineation of the TIS, in sectoral and in spatial terms, is presented in Figure 4.1. The TIS has evolved through the interaction of different types of actors (capital goods suppliers, customers, research institutes, etc.) originating from the coal, petrochemical, oil, pulp and paper, automotive, forest, agriculture and energy sectors, each making a contribution to the evolution of the design space. In terms of spatial delimitation, the case of analysing the role of system builders for the emergence of an industry with the capacity to realise the potential of biomass gasification in EU is, naturally, a single case study.

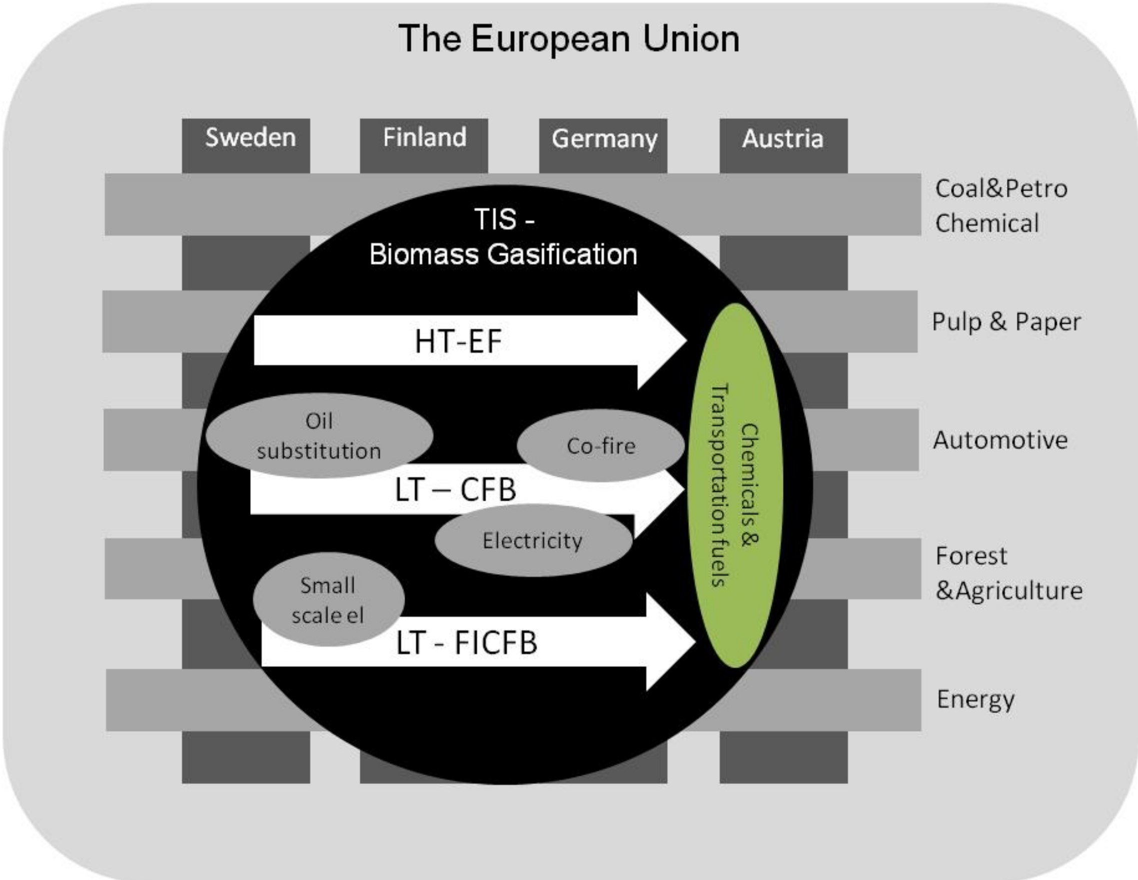

Figure 4.1: The delineation of the TIS in Europe and the four case study countries.

However, for operationalising a single case study on biomass gasification at European level, a breakdown into four country-specific case studies was, for two main reasons. First, the EU level has not been the dominant institutional context influencing the evolution of the field until 2003; rather, it has been led by various different national or even regional contexts. The dominant structure in which the actors are embedded and forced to interact would, therefore, be national rather than European. Second, when reviewing the technology (see Chapter III), it became obvious that the development leading up to the most advanced biomass gasification projects in existence today was concentrated in four countries: Sweden, Finland, Germany and Austria. In total, nine pilot or demonstration plants in Europe are under construction in these countries.

Chapters V-VIII will, therefore, focus on the evolution of the TIS in the four above-mentioned countries (see Figure 4.1). Within each national context, research questions 1-4 will be addressed, providing an opportunity to analyse current system weaknesses and limits to realising the TIS within a national framework. This will be followed by a cross-country analysis in Chapter IX.

For analysing the evolution of the TIS in the four case study countries, a historical narrative has been constructed for each case. Flyvbjerg (2006) argues that such a narrative should focus on the evolution of the relationship between actors and other structural elements. Such a focus makes it possible to trace the emergence of the key processes for innovation and diffusion (functions), the role of exogenous factors, and the role of system builders and other actors in the emergence of the TIS.

As appropriate, each country narrative was divided into one or several episodes—where each episode is dominated by specific patterns of interaction between the structure and the functions (Suurs et al., 2010). Due to the long history of biomass gasification in Sweden and Finland, it was possible to distinguish several episodes that have been important in leading up to the development of the current projects. In Germany and Austria, only one major episode specific to biomass gasification could be discerned in each country, as the history of biomass gasification is relatively short there. Additionally, in Germany the current projects either have a history in fossil gasification (as outlined in Chapter III) or stem from previous developments in the other countries.

The downside of restricting the analysis to four countries is that important research and development work that may be ongoing in several other countries in Europe risk being downplayed or even missed. However, a thorough analysis of ongoing research and commercialisation activities in the field of biomass gasification was performed at the start of the project. As such, the risk that there would currently be other and more relevant projects than the nine outlined in Chapter III is viewed as minimal.[96] The possibility of new projects "popping up" is of course possible, but such projects take considerable time to develop and are not likely to progress further than the nine I have selected within the time frame of this research project.

4.3 The evolution of the research project: Data collection, selecting and identifying the projects

Writing a book is a significant and time-consuming task. In this specific case, it has taken almost four years. The time spent researching and writing can be divided into three major phases, including the final phase, in which all the material was edited and re-written into what constitutes this book.

The first phase began in March 2007, when I visited an industrial conference in Stockholm on the topic of biomass and the poly-generation of fuels, electricity and other chemicals. In this phase, I focused my efforts on understanding the technology of biomass gasification. Giving my background in electrical engineering rather than chemistry, this was a significant and difficult task. In order to overcome this initial barrier, an extensive technical literature review was conducted in combination with two formal interviews with Christopher Higman (2007), who is an independent consultant and co-author of the book "Gasification"[97], and Ekbom (2007), who is Technical Director at a consultancy firm (Nykomb Synergetics) in the field of gasification, thus both are well-known and reputable gasification experts.[98] In addition, I attended a total of seven industry conferences between March and August 2007 on the topic of both fossil and biomass gasification. The conferences became an important part of the method for understanding past and current developments in biomass gasification, and enabled me to make sense of the literature I had read. They also allowed me to discuss

[96] In addition, if the activities in other countries are important to the commercialisation of the field, they are likely to collaborate with at least one or several of the nine commercialisation projects and would therefore also be covered.

[97] Higman, C., van der Burgt, M., 2003. Gasification. Elsevier Science, Burlington., and Higman, C., van der Burgt, M., 2008. Gasification. Gulf Professional Publishing, Burlington, USA.

[98] The technical review focused on the evolution of the design space of biomass gasification, its relationship to fossil gasification, and past, present and potential applications and markets, as described in Chapter III.

technical aspects of biomass and fossil gasification systems with experts and to make initial contacts for future interviews (see Table 4.1 for a list of conferences attended during the entire project).

Table 4.1: Conferences and seminars.

1	Elforsk Seminarium Biokombinat 2007, February 28, Stockholm, Sweden.
2	Energitinget 2007, March 20-21, Stockholm, Sweden.
3	15th European Biomass Conference & Exhibition 2007, May-8, Berlin, Germany.
4	2nd International Freiberg Conference on IGCC & XtL Technologies 2007, May 8-12, Freiberg, Germany.
5	SYNBIOS II 2007, May 23-24, Stockholm, Sweden.
6	Nordic Bioenergy 2007, June 11-13, Stockholm, Sweden.
7	2nd European Summer School on Renewable Motor Fuels 2007, August 29-31, Agricultural University of Warsaw (SGGW), Poland.
8	12th REFORM Group Meeting, Schloss Leopoldskron 2007, September 24-28, Salzburg, Austria.
9	DIME International Conference, "Innovation, sustainability and policy" 2008, September 11-13, GREThA, University Montesquieu Bordeaux IV, France.
10	Seminar at the Swedish Energy Agency 2008, October 27, Eskilstuna, Sweden.
11	Seminar at the Swedish Energy Agency 2009, April 27, Eskilstuna, Sweden.
12	AES Conference 2009, May 6-7, Katrineholm, Sweden.
13	SYNBIOS III Chalmers 2009, May 28-29, Göteborg, Sweden.
14	2nd Stakeholder Plenary Meeting of the European Biofuels Technology Platform 2009, January 22, Diamant Conference Centre, Brussels, Belgium.

At the outset of the project, I had decided to include only Sweden and Finland in the study. An additional objective of the technology review was to identify which projects in Sweden and Finland should be included. It was also of interest to gain, at least tentatively, an overview of how the projects in Sweden and Finland related to other biomass gasification activities in the world.

In order to generate such an overview and select projects, a database was constructed to include all of the major pilot, demonstration and commercial gasification plants that had been constructed between 1970 and 2007. The database was compiled from data made available in various publications and online databases. The main data sources were IEA task 33: Thermal Gasification of Biomass, in Babu (1995, 2005, 2006) and IEA (2001). Additional data came from GASIF (2004), Knoef (2005), Kurkela (1989, 2002), Palonen (2006), Larson et al. (2003; 2006), Olofsson et al. (2005), Marbe (2005) and the online database: www.gasifiers.org. As a result, a relatively comprehensive database with 123 entries could be constructed using what is believed to be the major plants aimed at technology development and commercial operation that have been constructed around the world. However, the data is obviously skewed towards Europe and the USA, since almost all data has been published by European and American authors with a focus on their context.[99]

The analysis of the database revealed that few of the 123 plants had been constructed or were under construction for realising synthetic fuels from biomass gasification.[100] The activities that had taken place and were currently under development in Europe, were concentrated to Sweden, Finland, Germany and Austria. In total nine prominent projects could be identified in these four countries and the study was consequently enlarged to include also Germany and Austria to capture the development of the field for the entire European Union (see Chapter III). The nine projects were verified as the most advanced demonstration projects for commercialising biomass gasification via the two initial interviews with gasification experts, as well as through informal interviews at the above-mentioned industry conferences. In addition, the relevance of the selected projects has been verified through-out the project as interviews have been conducted. I am therefore confident that the European development of the commercialisation of biomass gasification is well captured by studying the nine projects outlined in Chapter III.[101]

When an analysis of the knowledge field of biomass gasification was made and the database was constructed, it was relatively easy to identify which initial actors needed to be interviewed in the various cases. Two sets of actors were identified as important to interview.

[99] In addition to the 123 entries, there are thousands of rice husk gasifiers operating in Southeast Asia and an unknown numbers of other small-scale, fixed bed gasifiers all over the world, which have not been reported in the above-mentioned articles and sources (Knoef, 2005). These are, however, of little interest for the purpose of this thesis and no further efforts have been made to make the database complete with respect to fixed bed gasification.

[100] Other alternative designs for biomass gasification were thus considered when constructing the database such as fixed bed gasification systems for electricity generation. It was decided later to exclude these designs from the study since it would have made it too broad.

[101] In addition to the nine projects, there are highly interesting activities taking place at many universities and technical institutes around Europe. My impression is that the primary focus of these is not to demonstrate the complete process of biomass-to-liquids production, but rather some of the specific technical aspects that may also be necessary.

The principal actors in the nine projects were targeted first. These were typically capital goods suppliers, start-up firms, technical research institutes or universities who pursued project development in alliance with other actors. The method of "snowballing" (Kvale, 1997) was used as a complementary method for generating interviews with additional actors involved in the project and other actors whose support was identified as pivotal for achieving commercial success of the technology. Hence, for each project and country, a range of interviews were conducted with actual and potential capital goods suppliers, customers, consultants, universities, institutes, lobbying organisations and governmental agencies with an interest in developing the technology.

Second, a number of additional European actors were identified from a "knowledge perspective", even if they were not currently involved in any biomass gasification project. These actors were typically incumbent capital goods suppliers with previous experience in biomass gasification, or with proprietary rights over coal-based gasification technology that could potentially be used for biomass along the three trajectories already outlined in Chapter III. They were possible to identify from the database, which had been constructed based on biomass gasification plants, as well from the GASIF database (2004, 2007) and through attending industry conferences such as the 2nd International Freiberg Conference on IGCC & XtL Technologies in Freiberg, Germany, May 8-12, 2007. Interviews were also set up with these actors to explore their perspectives on biomass gasification.

The second phase was initiated already as early as September 2007, when the first interviews for the first case study were initiated. In total, 89 interviews[102] were conducted in the four countries (see Table 4.2), not counting numerous shorter informal interviews during conferences. The number of interviews has primarily been determined by the number of key actors contributing to the development of the TIS in each country and when a reasonable saturation of information was reached (cf. Kvale (1997)). To a lesser extent, the number of interviews was limited by the time and resources available and the willingness of individuals to participate in the study. In only a few instances, individuals were impossible to reach or refused to participate in the study. In such cases, it was possible to compensate by

[102] In addition, I refer to interviews conducted by Staffan Jacobsson and Anna Bergek in previous projects, and interviews conducted while being a guest researcher at Zhejiang University, Hangzhou in November 2009.

interviewing others from the same organisation or those who had access to similar information.

Table 4.2: Number of formal interviews conducted in the four case study countries.

	Sweden	Finland	Austria	Germany	Total
Interviewees	27	21	12	29	89

All of the interviews were semi-structured, and the interviewees were given ample time to tell their stories, based on a set of questions. The questions were derived from the purpose of the thesis, based on the emerging framework (which later became Chapter II), but were also adapted to the type of actors that was being interviewed (e.g., capital goods supplier, potential customer, university) and their role in the innovation process. The questions were also based on information derived from previous interviews and other questions that may have emerged during the study. The overarching focus, however, was ensuring that each interviewee could contribute to telling the story of biomass gasification in the different countries, and could verify important statements that other actors had made. As such, the interview guide has been a dynamic document and has therefore not been appended to the thesis.

Almost all interviews were recorded and careful notes were always taken. In most cases, the recording was checked against the notes, which were improved where necessary. Covering all topics during the interviews usually required 1.5-2 hours, but in many cases it took even longer. Hence, three-hour interviews were quite common. In a few cases, the interviewees were pressed for time or not very talkative, and only a few questions could be asked in a time frame of approximately 30-40 minutes.

Initially, the interviewees were not offered the chance to identify themselves as anonymous; this was accepted by all interviewees except two. Instead, all interviewees were offered to review and comment on the information and statements made during their interviews before the publication of this thesis. This proved to be a very good method for the first paper, Hellsmark and Jacobsson (2009), since we received many helpful comments from the interviewees, on both general and specific issues. Since the interviewees were not anonymous, I believe that this method motivated them to read the material more carefully than they otherwise might have done.

The method has, therefore, also been used for the chapters covering the case study countries, Chapters V-VIII, and has generated broad responses from the interviewees in all the countries (from approximately 25 individuals). With only one exception (referring to the early history of biomass gasification in Finland), no major critique has been raised. All comments have been addressed and it has been possible to make the required corrections without any substantial editing.

In addition, Chapters VII-VIII on Sweden and Finland were sent to three experts with a long history within the field for comments. They had previously not been interviewed since interviews had been made with others with similar knowledge and experience (but are now counted among the 89 interviewees above). Chapter III was carefully reviewed by Christopher Higman. These four experts have contributed to this study with detailed and general comments on its content, which have increased the quality and reliability of the study.

In order to be able to construct the different cases, it was necessary to use various data sources beyond interviews (cf. triangulation (Yin, 2009)). Additional information was thus collected on four different levels. First, additional background data on the interviewees themselves were gathered before each interview, including his or her relationship to the project in question and related activities which may have been of direct interest. Second, data were collected on the specific projects and technologies with regard to their desirability, potential cost efficiency, well-to-wheel analysis or other assessments made on the project itself or the trajectory as a whole. Third, for each case study country, I surveyed reports, papers and other legal documents on the specific institutional framework concerning the electricity and fuel markets, policy strategies and assessments thereon, and the countries' performance in relation to EU biofuel targets. Fourth, various documents published by the EU such as the EU directives on renewables were used.

The first case study conducted was in Austria. It was a logical starting point, because it is the smallest of the case studies; it only includes one project, relatively few actors, and the country has a relatively short history in terms of biomass gasification for the production of transportation fuels. Since it is small, hypotheses and ideas for the other countries could relatively quickly be generated.

When the TIS framework was confronted with the empirical reality in Austria—which was dominated by a strong individual acting as a system builder—it became obvious that the framework had to be strengthened with respect to the role of the individual acting as the system builder. The concept of "transformative capacity" was borrowed from Giddens (1984a) as a means of analysing the nature of and limits to the system builder's ability to contribute to the formation of a TIS. In the paper, it was argued that "If the limits to an individual's transformative capacity are adequately identified, we can make a clearer separation between the role of individual system builders and that of public policymakers and specify when the latter need to step in to address system weaknesses that are beyond the individual's sphere of influence." (Hellsmark and Jacobsson, 2009, p. 5597).

The Austrian case is very much an extreme case, where one individual had a significant impact on the development of the TIS. Nevertheless, it illustrates the value of having a distinctive, actor-oriented point of departure, and that such a point of departure can contribute to the analysis of the formation a TIS and the potential role of policy in stimulating what may be considered a strategically important field of knowledge. The observations made in Austria have thus strongly influenced the rest of the study and the formulation of the specific research questions presented in Chapter II.

Following the Austrian case, it was important to start with Germany as soon as possible since it was the largest case of them all. It included the largest number of actors and several pivotal projects for developing the TIS of biomass gasification. The German case was also dominated by several actors not currently part of the TIS, but with extensive experience in fossil gasification—which may also prove important for the development of biomass gasification.

The Swedish and Finnish cases were initiated as the interviews for the German case study were nearing completion. The interviews for Sweden and Finland were done very much in parallel, since the history of the development of the TIS in the two countries has largely been mutually dependent.

Each case study required many back-and-forth trips to these countries, since each trip (except the last) generated new insights, questions and actors that should be interviewed. The observations made in each case have been continuously summarised in non-published case study reports to keep track of the evolution of the history in each country and to be able to construct the stories as they unfolded. These reports have served as the basis for writing Chapters V-VIII.

Preliminary versions of the chapters in the thesis were presented and commented on in various fora. The first version of the technology chapter was presented at the 12th Reform Group meeting in Salzburg, Austria, in September 2007. The Austrian case was presented twice, first as a conference paper at the Dime Conference in September 2008, in Bordeaux, France, and the policy conclusions from the case were discussed with policymakers at the Swedish Energy Agency at a seminar in October 2008. A synthesis of tentative conclusions for all four countries was presented at yet another (and larger) seminar for policymakers at the Swedish Energy Agency in April 2009. The preliminary policy conclusions for the European Union outlined in Chapter XI were presented and commented on during a conference arranged by the Swedish Energy Agency in May 2009 (see Table 4.1). Comments received were incorporated into this thesis alongside those made from reviewers. These comments have significantly contributed to the final version of thesis.

Of course, it would have been ideal to discuss the preliminary conclusions in closer cooperation with policymakers in the three other countries and at the European Union level. However, such meetings were not set up due to lack of time. Nevertheless, it is still argued that the method used increased the reliability and validity of the study as a whole.

Part II

Case studies

Austria

Chapter V[103]

Austria

The Austrian history of biomass gasification is a long one in which extensive experimentation has taken place since the early-1900s. These experiments have been directed towards developing mobile gasifiers such as those developed in Sweden during the Second World War (see Chapter III), as well as stationary applications. If developed, the stationary small-scale technologies could play an important role in Austria since there are many small district heating (DH) networks that are not currently being utilised for power production, as conventional CHP technologies cannot be made competitive in small sizes.[104]

During the 1990s, there was renewed interest in increasing electricity production from various new renewable resources such as wind, solar, small-scale hydro, and biomass. This interest was followed up by a wide range of development incentives provided by Austria's provinces.

In the light of the desire to increase electricity production from renewable resources, the Technical University of Vienna (TU Vienna) developed the fast internal circulating fluidised bed (FICFB) gasification process to enable electricity production based on small DH networks in the early-1990s. At the centre of this development, and of this case, is the individual and academic system builder in focus, Professor Hermann Hofbauer from TU-Vienna. Largely due to his efforts, a network of advocates for the technology could be formed and a demonstration plant was built in the town of Güssing in 2001.

Over time, further incentives to continue experimenting with the technology were provided by the EU biofuel Directive 2003/20/EC, and the actors began exploring the technology for

[103] Most of this chapter was previously published in Hellsmark and Jacobsson (2009).
[104] Even if fixed bed gasification has been of historic importance in Austria, it has little to do with what is currently happening there and will, therefore, not be further be dealt with in this section.

the poly-generation of transportation fuels, electricity and heat.[105] Since then, this has developed into one of the nine most promising projects for realising biomass gasification for the production of second-generation transportation fuels and other chemicals in Europe.

This chapter is divided into three main sections. The first section focuses on the interactions between actors and the characteristics of the emerging technological innovation system (TIS). The focus is on how the system builders act to create the emerging structure of the TIS, both by building the structure directly and by strengthening the various functions outlined in Chapter II.

The second section provides answers to the research questions (as specified in Chapter II). The discussion will start with discussing who have acted as the system builder and describe the nature and extent of his transformative capacity. The focus then shifts to analysing and explaining the limits of the system builder's transformative capacity, identifying main system weaknesses, and discussing the potential role of the system builder and policymakers in addressing these weaknesses. The third section of this chapter presents the main conclusions.

5.1 The formation of a biomass TIS in Austria

This section contains a descriptive analysis of the first 15 years of the emergence of an Austrian TIS centred on fast internal circulating fluidised bed (FICFB) biomass gasification. The analysis is divided into three parts. The first part covers the early network formation leading to the construction of the first plant in 2001. The second covers knowledge development centred on this first materialisation of the technology. The third covers the processes by which a second plant was constructed, as well as changes in the institutional context that impeded further market formation.

[105] Domestic production of first-generation biodiesel from food crops has existed since the early-1990s (Wörgetter et al., 2002; EC, 2003). However, the directive mandates all member states to increase their share of biofuels or other renewable fuels in the transportation sector by 2 percent by 2005 and 5.75 percent by 2010 (EC, 2003). Austria has been one of the few countries in Europe to have significantly increased their production and consumption of first-generation fuels. In 2007, the share of transportation fuels was 2.77 percent, compared to the EU average of 2.6 percent, and where almost all fuels consumed were domestically produced from agricultural crops (Eurostat, 2009). Austria is, however, far from reaching the 5.75 target by 2010. The new directive 2009/28/EC, which mandates a 10 percent share by 2020, will increase the incentives for renewable transportation fuels even further.

5.1.1 The formation of a network and the construction of the Güssing plant

This story begins with Hermann Hofbauer, Professor of Chemical Process Engineering and Fluidisation at the Department of Chemical Engineering, Technical University in Vienna. Hofbauer finished his PhD thesis on fluidised bed coal gasification in 1983. Ten years later, his curiosity drove him back to this technology but this time using biomass as a feed-stock, since he was convinced of its usefulness for environmental reasons (*influence on the direction of search*). He employed a PhD student who built a laboratory-scale (10kW) gasification process for biomass, drawing on Hofbauer's previous work *(knowledge development*) (Hofbauer, 2007).

Christian Aichernig was the head of research and development at the leading capital goods producer Austrian Energy & Environment (AE&E) in the 1990s. AE&E mainly provided gas cleaning, waste incineration equipment, and fluidised bed boilers for biomass and coal, and was successful at the European and global levels. AE&E collaborated with Professor Hofbauer in flue gas cleaning technology, and also co-funded his research on biomass fluidised bed gasification. With support from AE&E (*resource mobilisation*), the 10kW gasifier was scaled up to a 100kW plant (*entrepreneurial experimentation*) for the purposes of supplying heat and power on a small scale.[106]

At the end of the 1990s, Professor Hofbauer went to an annual biomass conference held in the town of Güssing. He gave a lecture on the novel technology he was working on and argued that it was ready to be scaled up. This was timely, as the Mayor of Güssing was looking for a novel technology to supply heat and power to the town. Güssing had well developed norms (informal institution) about being self-sufficient when it came to its energy supply and that the supply should be based on renewable energy sources. It had already built a biodiesel plant as well as a district heating system, and lacked only a supply of renewable power to become independent.[107] The Mayor and the chief technician, Reinhard

[106] There is a small scale trajectory for district heating in Austria. There are about 1,000 small DH systems (2-4 MW heat), each of which could provide the base for an installed capacity of 200-400 kW_{el} of electricity (Kopetz, 2007). These systems are situated in villages that are distant from the natural gas grid (Lauber, 2007).

[107] Two Swedish pioneers (the district councils of Enköping and Växjö in Sweden) in conventional biomass CHP had a similar driving force (Hellsmark, 2005; McCormick and Kåberger, 2007).

Koch, liked Professor Hofbauer's technical solution and decided to build such a plant in Güssing.

Professor Hofbauer then approached Aichernig at AE&E to determine if they could deliver the plant. Aichernig was happy to undertake the industrial project but had to overcome a significant obstacle—convincing AE&E's management to supply a technology at a scale that was much smaller than their normal plants (which started at 30MW fuel power).

Management, however, eventually agreed to construct the plant as a research and development project. At that time, management saw biomass as the future for fluidised bed technology but there were still uncertainties regarding exactly how biomass would be used. Gasifying the biomass was one of several options. It was, in principle, an attractive technology, as it promised high efficiency electricity production and a good heat supply. Furtheremore, AE&E had a good relationship with Professor Hofbauer. As a result, it was seen as an interesting technology to experiment with, particularly since demand for conventional boilers was low at the time. The decisive factor, however, was that Güssing was a real project and they could receive substantial subsidies for the engineering work (Kaiser, 2008) (through RENET, see below). After two years of work, TU Vienna and AE&E had defined the project and the contract was signed in 2000.

Another major hurdle was financing the project, although it was eventually possible to mobilise the financial resources required. The most important source was a government risk absorption scheme that made it possible for Güssing to secure a bank loan where the risk was absorbed by the lender.[108] The loan amounted to about 45 percent of the total funding (Aichernig, 2007). The rest was largely provided by the EU and Austrian regional development funds. These were accessible because Güssing was considered to be in an underdeveloped region.[109] As a result, large subsidies were awarded for the construction of this demonstration plant (*resource mobilisation*).

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[108] As the lender, FFG absorbed the risks and the bank did not need to add a risk premium. Additionally, if the project failed, the loan would not have to be repaid.

[109] Güssing is located in Burgenland, which is a small province in southeastern Austria. With the fall of the Iron Curtain and access to EU regional development funds, Burgenland has invested heavily in bringing people and

Parallel to his work in defining the project with AE&E, Hofbauer was also the driving force in the organisation of a "Competence Network for Energy and Biomass" consisting of Güssing, AE&E, TU Vienna and the regional electrical utility Energie Versorgung Niederösterreich. The network received funding for seven years from the Ministry of Economics and Labour to establish a competence centre called RENET, which became the first of its kind in Austria (institutional change). Professor Hofbauer was appointed its spokesman and scientific director.

The formation of RENET was important not only for providing funding for AE&E, but for two additional reasons as well. First, Professor Hofbauer was able to expand his group from one PhD student to over ten PhD students and one to two senior researchers working full-time on biomass gasification. In addition, many Master students were given the opportunity to write their diploma theses on biomass gasification. Therefore, RENET enhanced *knowledge development* considerably and provided a base from which human resources could later be mobilised (*resource mobilisation*).

Second, an organisational structure was established within the RENET programme that enabled the work to progress very quickly (Hofbauer, 2007), in which the plant operator at Güssing collaborates with the scientific staff and industrial partners. This structure allow the three partners to test ideas and learn from each other in unique ways, and has been one of the most important factors for the fast progression of the work at Güssing (Hofbauer, 2007) (see more below).

At the beginning of 2001, it became evident to Christian Aichernig that the owners of AE&E, Babcock would go bankrupt. In response, the gasification network, along with its key individuals Professor Hermann Hofbauer, Reinhard Koch, the mayor of Güssing, and Christian Aichernig, met to decide what to do to secure the survival of the project. They decided to form a new company, Repotec. When Babcock went bankrupt in mid-2001, Repotec had, therefore, already been formed.

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companies to the region. Renewable energy, coupled with the wish to become self-reliant, has been one method for developing the region.

After the bankruptcy, AE&E was acquired by an Austrian investor (Mirko Kovats) who chose not to renew the contract with the Güssing plant. AE&E was thus deliberately de-linked from the Güssing plant. Instead, Repotec received the Güssing contract and a number of engineers formerly at AE&E went to work for Repotec.[110] The Güssing plant was finished in 2002 and, with its completion, the first major *entrepreneurial experimentation* for biomass gasification based on fluidised bed technology in Austria had been carried out.

5.1.2 Stalling markets despite good incentives, and extensive knowledge formation

Austria implemented a national feed-in law in 2002 to promote the diffusion of technologies using renewable energy sources. Rapid diffusion followed for conventional biomass-fuelled plants (CHP and condense) as well as wind turbines and solar cells.[111] With the new law, electricity generated from biomass was granted a fixed price of up to €0.16/kWh for 13 years of operation. The highest rates were issued to plants of up to 2MW of electricity and that were running on wood chips or straw. The Güssing plant benefited from this since it was designed for 2MW of electricity, which led to an additional source of revenue.

With the new high feed-in rates for electricity from biomass and the higher electrical efficiency that was expected with the Güssing technology (as compared to conventional CHP plants), the future for the technology looked promising and it received significant attention. Indeed, following the construction of the plant (*materialisation*) Güssing received a very large number of visitors (Koch, 2007), some of whom explored the option of building a similar plant (Aichernig, 2007; Hofbauer, 2007). However, only one eventually materialised in Austria (so far, writing in 2010), while a few plants are planned in Germany,[112] France and Sweden (see Chapter VII).

The market has been very slow to materialise in Austria and elsewhere for a number of reasons. The first reason is likely the relative immaturity of the new technology when

[110] The intellectual property rights were owned by TU Vienna and AE&E. Repotec has access to the part owned by TU Vienna. The part owned by AE&E went into reconstruction following the bankruptcy. Repotec has a licence agreement with AE&E.

[111] Production rose from 0.6TWh in 2002 to close to 4TWh in 2006 (E-control, 2007).

[112] At least one plant in Germany is under construction in the city of Ulm by the regional utility Stadtwerke Ulm for combined heat and electricity production (Vitek and Sommer, 2008).

marketed in 2002. It had low availability, high operating costs due to the need to use high quality and expensive feed-stock, and the need to optimise, change or adjust several of the plant's components to obtain stable and cost efficient operations—which in turn required more and increasingly specialised staff. These initial deficiencies resulted in a high price for the electricity in relation to conventional technologies.

However, the price-performance ratio of new technologies is often poor initially but improves with accumulated experience. At this time, at least two techno-economic assessments pointed to biomass gasification as " … sufficiently advanced to justify [...] pre-commercial plant(s)" (Bridgwater and Bohlár-Nordenkampf, 2005, p. 341). It was also argued that the erection of such plants was the only way to resolve the remaining uncertainties (Bolhàr-Nordenkampf, 2004; Bridgwater and Bolhàr-Nordenkampf, 2005).[113] Still, there were disagreements about whether these uncertainties could be resolved or not, and AE&E's standpoint was a very cautious one.

The second—and more fundamental—reason was the absence of a larger company that was prepared to tackle these uncertainties and commercialise the technology. Although it is common for new technology-based firms to drive discontinuous technical changes (Utterback, 1994) they sometimes need to enter alliances with incumbents that possess complementary assets; such alliances are common in the biotechnology industry. Similarly, but for partly different reasons, new technology-based firms cannot "go it alone" in the power plant industry. In this industry, financial guarantees are given to back up a contract where the technology supplier assures a certain level of plant availability. If the technology is not available at the specified rate, the technology supplier must pay a fine specified in the contract, which usually corresponds to the losses associated with the lower level of availability (or part of these losses). Repotec is a small firm with five employees and cannot, therefore, provide such financial guarantees. Nor does it have the manpower to build a complete plant.

[113] As described later in this section, extensive research and development has addressed many of these immaturities, improving the overall price-performance ratio and allowing for the exploration of new and more valuable products than heat and electricity such as BioSNG.

For these reasons, Repotec needed a partner. According to Bohlàr-Nordenkampf (2007) and Kaiser (2008) at AE&E, as well as Aichernig (2007) at Repotec, the original agreement was that Repotec would find the customers, design the plants and be the technology supplier, while a reconstructed AE&E would be the general contractor who provided financial guarantees and built the plants.[114] For AE&E, such an agreement would be a way to stay in contact with a technology for which they had competencies and a patent (Kaiser, 2008).

As yet, the agreement has not led anywhere, for two main reasons. First, there was a perceived lack of clear demand for gasification plants from customers (Kaiser, 2008). However, a contributing factor to the poor demand may have been the recommendations by AE&E to potential customers to build a conventional combustion plant instead of a gasification plant (Hofbauer, 2007). Contrary to earlier expectations, AE&E had come to view gasification technology as less suitable for CHP purposes than steam boilers. Boiler performance had improved (e.g., through flue gas condensation and higher pressure), they were cheaper, and were a proven technology option, which allowed AE&E to provide guarantees for it that would be very risky in the case of gasification technology (Kaiser, 2008). The technical risk, therefore, would have had to be shifted from the potential customer and technology supplier to society at large.

The second reason was the now booming market for conventional boilers, which meant that AE&E, as opposed to the time when the Güssing plant was built, had no spare capacity to work with gasification projects. As a consequence, the *direction of search* for AE&E was firmly set on improving conventional steam cycle technology as a way to use biomass as a means to reduce CO_2 emissions (Kaiser, 2008). AE&E did not, therefore, become the industrial partner that could help commercialise and further develop the Austrian gasification knowledge base.

The strong economic incentives provided by the feed-in law and a general interest in the technology from investors did not result in *market formation,* due at least in part to AE&E's strategic decision to keep a distance from the technology. It is, of course, very common for

[114] Kaiser (2008) also meant that if AE&E was not interested in building a plant, Repotec could do it but had to pay a fee to use the patent.

incumbents to make such strategic choices early in a technology's development. Whereas the literature points to a set of reasons connected to mental filters and various sources of inertia as explanations (e.g., Utterback, 1994; Christensson, 1997; Tripsas and Gavetti, 2004), such a choice may be quite reasonable—why invest in a risky and poorly performing new technology when the market for conventional combustion plants is booming? Being the leading capital goods supplier in Austria, however, this strategic choice most likely weakened the legitimacy of the technology and obstructed the development of the TIS (*legitimation*).

Even if *market formation* was poor, *knowledge development and diffusion* was strengthened. *Knowledge development* of the FICFB technology in Europe is centred on the Güssing plant, which is used as an experimental plant in addition to being a commercial one.[115] Based on the RENET programme and complementary projects, advancements have been made in two main areas of research: plant availability and the costs associated with plant operation, and new and more advanced applications.

In the first area of research, plant availability has been greatly improved[116] and the work on reducing costs has involved minimising the amounts of waste heat, using cheaper feed-stock and improving gas cleaning (Koch, 2007). The second area of research involves different methods to upgrade the product gas from the current use of electricity and heat generation to more advanced applications that require a cleaner synthetic gas. The ultimate goal of the research is to develop a poly-generating plant that produces heat, electricity and a third high value product such as FT-diesel or BioSNG (Hofbauer, 2007).

The main source of funding for the project is the EU, RENEW, Demo BioSNG, and a national programme called "Energy Systems of Tomorrow" (Institute of Chemical Engineering, 2006, 30). The various research experiments are largely conducted as part of various international research and development projects.[117] Indeed, the Güssing plant, with TU Vienna as a

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[115] More recent experiments with the technology have been initiated at the technical research institute ZSW in Stuttgart (see Chapter VI) and at Chalmers University of Technology in Göteborg (see Chapter VII).

[116] Operating experience as of mid-2007 surpassed 29,000 hours for the gas engine and 33,000 hours for the gasification process, and total plant availability has been established at well over 90 percent.

[117] The projects that are running at the plant are (autumn 2007): **BioFiT** – an EU-project within which the coordinator is VW and includes partners such as Shell, Daimler and Volvo. The objective in BioFiT is to develop the FT-synthesis from biomass gasification. Since 2006, they have had a pilot facility at Güssing where they are testing a range of different catalysts to produce FT-diesel (Koch, 2007). **BioSNG** – The work with

partner, has been put at the centre of a European research and development network in gasification technology. The boundaries of the technology at Güssing are continuously tested as a result of this constant *knowledge development*. And a third and high value BioSNG product was demonstrated by the end of 2009. With the establishment of RENET and the different international partners, this knowledge development has been diffused to a large number of actors. However, most of these are located in other parts of the EU, and a critical question for Austria is the ability of the Austrian TIS to benefit from this knowledge development.

5.1.3 Construction of a new plant in Oberwart and changes to the feed-in law

Repotec completed the pre-engineering process and managed to obtain all of the necessary permits to build a second plant in Oberwart, 30km from Güssing, just before the feed-in law expired at the end of 2004. The work was to be undertaken on behalf of the local utility BEGAS. When it was time to negotiate the contract, BEGAS wanted a guarantee of 7,500 operating hours (Hofbauer, 2007). Repotec felt this was slightly high and only wanted to guarantee 7,300 hours (Aichernig, 2007). Ultimately, they did not reach an agreement.[118] Instead, another company, Ortner, was awarded the contract. This appears to have come as a surprise for most people in the gasification network in Austria, since Ortner had not been

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developing a SNG from the producer gas at the plant commenced around 2003. It started with a small test rig in the 2kW scale (Aichernig et. al. 2004). In 2007, they began building a 1MW BioSNG demo plant at Güssing, where they will produce a SNG with 97 percent methane content (Koch, 2007; Hofbauer, 2007). The main scientific partner is Paul-Scherrer Institute (PSI) in Switzerland and the main industrial partners are Swiss Electric and Conzepte Technik Umwelt AG (CTU). **AER** – The objective with the Absorption Enhanced Reforming (AER) project is to increase the hydrogen content in the gas to approximately 70 percent (Marquard-Möllenstedt et al., 2004). The project is funded partly by the EU and is a co-operation between the Centre for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW) in Germany and TU Vienna. The cooperation started around 2003 and since 2005, the Güssing plant has been involved as a large scale test bed for the process. ZSW is the patent owner of the technology and is now aiming to build a 10 MW plant in the town of Göppingen (Specht and Zuberbuhler, 2007). **BioSOFC** – An advanced application of the producer gas in solid oxide fuel cell (SOFC) is researched in cooperation with Austrian Bioenergy Center (ABC) in Graz and the department of Energy and Process Engineering, NTNU, in Trondheim (Aichernig et. al. 2004). The idea is to use the gas in a SOFC to achieve a high electrical efficiency, above 43 percent, with a high total efficiency of above 80 percent. The SOFC can only be used if advances in high temperature removal of dust, chlorine and sulphur components can also be accomplished (cf. (Stanghelle et al., 2007)).

[118] Repotec argued that these types of discussions should not be central to a contract when the plant is based on gasification technology. They prefer the clients to be deeply involved with the technology and understand the risks. The technology of the Oberwart plant is not developed to the stage of, say, that of a steam turbine CHP. However, they guaranteed 7.300 hours, limited by conditions such as them performing the maintenance and that it could be reached within six months of operations (Aichernig, 2007).

involved in the technology development at Güssing and had no prior track record in gasification.

Ortner is an engineering company that normally does layout and design of large commercial buildings (including infrastructure such as piping). It has also developed expertise in environmental technologies such as waste-water treatment (Madl and Daxer, 2007). When its normal business was not performing well, however, it decided to diversify into power generation and constructed five plants between 2005 and 2007, four of which are based on biomass combustion of wood chips for CHP. It initially purchased all of the necessary equipment but has recently started producing the combustion chambers itself. In addition to biomass CHP, Ortner investigated the possibility of starting businesses in the field of alternative fuel. Consequently, it considered biomass gasification as a promising technology but moved into it more or less by accident when it was asked to construct the plant (Madl and Daxer, 2007).

For the construction of the plant, BEGAS provided the basic design to Ortner[119] but without first requesting Repotec's co-operation (Aichernig, 2007). From an outsider's perspective, this co-operation would appear to have been ideal, since Ortner is a general contractor that can build plants and have the engineering capacity and financial muscle for large projects but lack Repotec's experience in biomass gasification. By excluding Repotec from further work in connection with the Oberwart plant, the biomass gasification network was disrupted.

Ortner has high expectations for future business in the field. In 2007, it had three to four potential customers for similar plants, but need Oberwart as a show-case. In addition, it hoped to have a research and development project at the plant and build up its own knowledge on gasification. It is thus imperative for Ortner to succeed with the plant to be able to continue within the field.

[119] At the beginning of the project, Ortner was unaware that there was a patent pending on the technology held by AE&E. Ortner was then granted a licence for one plant using the patented technology (Bolhàr-Nordenkampf, 2008).

While Ortner is aware that it is taking a large risk, it is also taking action to minimise the risk of failure. The most important action is the collaboration (learning network) it has established with Professor Hofbauer at TU-Vienna, which has been formalised with meetings every two or three weeks during the early phase of plant construction. Professor Hofbauer has thus come to play a central role for ensuring the success of Oberwart, compensating, at least in part, for the above-mentioned disruption of the network. The significance of this goes far beyond the success or failure of the Oberwart plant—Professor Hofbauer is well aware of the powerful negative effects that failed experiments can have on the *legitimation* of a new technology. Two such experiments are Arbre in the UK and Värnamo in Sweden (see Chapter VII), which involved BIGCC[120] technology in the late-1990s and which have obstructed further financing and development of that technology (Hofbauer, 2007).

Efforts to build the TIS for gasified biomass in Austria, however, ran into a new obstacle in 2006 when the feed-in law was revised. The initial national feed-in law of 2002 was successful in that it promoted a rapid diffusion of a range of technologies (Kopetz, 2007; Lauber, 2007). Yet, the feed-in rates were high and there was a strong back-lash from heavy industry, in particular the pulp and paper industry,[121] which aligned itself to other organisations in an attempt to revise the law (Kopetz, 2007; Lauber, 2007). The back-lash was quite understandable and predictable, since the pulp and paper industry was excluded from receiving feed-in tariffs (despite a large production of biopower) but still had to pay the higher rates (Dworak and Zettl, 2008). The subsequent revision led not only to institutional uncertainty but, most importantly, to obstructed *market formation.*

The main change has been the introduction of a cap on the funding.[122] The annual additional support for the 2007−2011 period is only €17 million, of which 30 percent is for biomass-

[120] BIGCC (Biomass Integrated Gasifier Combined Cycle), which is a technology that potentially can increase the electrical net output (see Chapter III).

[121] The pulp and paper industry lobbied very hard against the feed-in law and succeeded in changing the regulations (Dworak and Zettl, 2008). The industry felt that the feed-in law was discriminating against the high level of bioenergy utilisation and the high energy efficiency efforts of the companies. In addition, an increased use of bioenergy was perceived as a threat to their wood supply (Dworak and Zettl, 2008).

[122] Even the Director of the Austrian Biomass Association, Heinz Kopetz, is in favour of a cap, except for smaller CHP plants, since there is no good technology for such applications and there is a worldwide market for those who develop it. For larger CHP plants, he suggests an annual cap of 20-40MW. The key reason for this is that there is a paucity of district heating grids and many new plants waste heat. He argues, convincingly, that

related technologies. Moreover, the number of years for which an investment is eligible for support was reduced.[123] Since the change in the law, business for gasification has stopped completely (Aichernig, 2007; Madl and Daxer, 2007) and has slowed down considerably for all other types of renewable power generation (Lauber, 2007). Instead, Ortner expects Germany and Italy to be its main future markets for the technology (Madl and Daxer, 2007). Repotec has also written off Austria as a possible future market and instead is hoping for the French, German and Swedish markets to materialise (Aichernig, 2007).

5.2 The system builders' transformative capacity, system weaknesses and the potential role of policy

In this section, the four research questions specified in Chapter II will be revisited. Answers to each question will be provided for the case of Austria by analysing the previously outlined history. The research questions were formulated as:

1) *Who act as system builders in the different national contexts?*
2) *What characterises the nature and extent of the system builders' transformative capacity?*
    a) *How do the system builders make use of the general structure in which they are embedded to form or strengthen the structure and the various functions of the TIS?*
    b) *To which extent do the system builders manage to strengthen the structure and functions of the TIS?*
3) *What are the limits to the system builders' transformative capacity and how can these be explained?*
4) *Given these limits, which system weaknesses remain to be resolved by system builders and policymakers on different levels (national and EU)?*

This section is divided into two parts. Research questions one and two will be analysed in the first, and research questions three and four in the second. The discussion will begin by

heat should be the main product and that power production should follow from heat production (Kopetz, 2007). However, a cap blocks the market for the novel technology of gasified biomass.

[123] The projects are awarded on a first-come, first-served basis, and a cap means that a project may not be funded. This is problematic, as the work to generate an application costs about 10 percent of the total budget for the project. Additionally, it takes longer and is more expensive to put together an application for a novel technology such as gasification than for one based on combustion. The new system, therefore, discriminates against new technologies (Achernig, 2007).

briefly discussing who has been acting as the system builders, and describing the nature and extent of their transformative capacity. The focus then shifts towards analysing and explaining the limits of the system builders' transformative capacity, identifying the main system weaknesses, and discussing the potential role of system builders and policymakers for addressing this weakness.

5.2.1 The nature and extent of the system builders' transformative capacity

With respect to RQ1, it has been illustrated that it is primarily Professor Hofbauer who acts as the system builder. Although the network that he has been instrumental in forming has conducted some system building activities, the focus of the analysis will be Professor Hofbauer. He not only initiated the formation of the TIS but remains very important to its further development.

As explained in Chapter II, the nature of the transformative capacity of the system builder is revealed by his/her ability to build and strengthen the structure and different functions in the formation of a new TIS. The limit to his/her capacity is, however, determined not only by the actions of the system builder but also by endogenous and exogenous forces at work that either pave his/her way or restrict his/her impact. The transformative capacity of Professor Hofbauer is far-reaching, and to some extent he has managed to strengthen all the key processes. There are, however, significant counter-forces that, at least temporarily, limit his transformative capacity by weakening some of the functions.

The nature and extent of Professor Hofbauers transformative capacity will be analysed by first describing how he has managed to strengthen the various functions of the TIS by making use of the general structure in which he is embedded. The analysis will then turn to describing the specific system dynamics between the functions and structure of the TIS, i.e. the motor of the TIS (Hekkert et al., 2007; Suurs, 2009), which has emerged as a result of his transformative capacity.

Influence on the direction of search

Professor Hofbauer is the dominant agenda-setting force with regards to technology choice, plant design and choice of application to be developed. Indeed, it was on his research that the plant concept and design was based. He has thereby set the general direction (technology trajectory) to which others also contribute. By defining the opportunity in the field, he has also made it attractive for firms to enter the TIS, both as customers (*market formation*) and as suppliers (*entrepreneurial experimentation*).[124]

His impact has been facilitated by the external factor "climate change debate" and the associated increased importance of the efficient utilisation of biomass. At the same time, the political debate in Austria has created controversy around using biomass for electricity production and the feed-in system was recently changed, such that it now discourages investors from entering the field. Additionally, combustion is the dominant substitute for gasification, and there remains very high demand for boilers and other such equipment. The strong demand in the conventional business has, of course, made the search for new and alternative technologies less attractive to the incumbent actors (Bolhàr-Nordenkampf, 2007).

Resource mobilisation

Professor Hofbauer has managed to attract several crucial resources for the further development of the TIS. Due to his longstanding cooperation with AE&E, he managed to secure funding for the first *entrepreneurial experiments*. Working with his contacts in AE&E, he helped convince management at the company to sign the contract for the first large-scale demonstration plant in Güssing, despite scepticism surrounding the new technology.

In terms of financing the *knowledge development* at the Güssing plant, he established RENET and became its scientific director. With the long-term financing provided through RENET, he substantially expanded his research in the field. With the RENET platform, together with the Güssing plant that is now part of the TIS structure, he attracted many European research programmes and partners that provided funding to further the technology development at Güssing.

His ability to create RENET was facilitated by a strong trend in public research and development policy (not just in Austria) to establish competence centres. This exogenous

[124] In an early phase, new problem and possible solutions are loosely defined, which means that no distinct "technology style" (cf. Hughes (1987)) or "dominant design" (cf. Utterback (1994)) is set. One of Professor Hofbauer's contributions has been to define one of three trajectories (see Chapter III) and to organise a knowledge network for the further development of this alternative.

factor strengthened the key process and enabled him to mobilise resources that, presumably, may not otherwise have been available.

Along with other actors, Professor Hofbauer also played a direct role in finding financing for the Güssing plant. The process of *mobilising the financial resources* for plant construction was facilitated by the location of Güssing in what is considered an underdeveloped region—allowing them to obtain funds for regional development that may not otherwise have been accessible.

There are also exogenous factor that weaken this key process and thereby counteract the efforts undertaken by Professor Hofbauer. In particular, the strong demand in AE&E's core business has made it very difficult for Professor Hofbauer to persuade it to contribute resources to the development of the TIS after the restructuring of the company. Instead, it has left the TIS for biomass gasification.

Entrepreneurial experimentation and materialisation

With the resources that Professor Hofbauer has managed to attract, he has considerably strengthened the processes of *entrepreneurial experimentation* and *materialisation* in Austria. He has played a significant role by directly or indirectly enabling all of the *entrepreneurial experimentation* that have taken place in the country.

Working with PhD students, he built the first 10kW and 100kW pilot plants, and was also highly involved in the design of the 10MW plant in Güssing. During construction of the second plant of the same type in Austria, he was active as the technical adviser to the plant constructor Ortner.

Since its completion, the Güssing plant has become a resource to which additional experiments can be connected. For example, there have been experiments with 1MW BioSNG, FT synthesis and advanced gas cleaning.

An exogenous factor that he could not influence was the acquisition of AE&E by the US-based company Babcock, which later went bankrupt. The network managed these events, however, by setting up a new company, Repotec, which took over the contract from AE&E and completed the plant construction.

Knowledge development and diffusion

Since he started with biomass gasification at the beginning of the 1990s, Professor Hofbauer has been able to significantly strengthen the process of knowledge development and diffusion. He started with one PhD student and has now about 20. Between 1991 and 2008, he supervised over 50 PhD students and 115 diploma theses. He has written, either by himself or in collaboration with others, 170 scientific reports, papers and book contributions, and has given more than 120 presentations on gasification or related subjects. All of these activities, as well as some consulting work, have diffused knowledge on gasification within academia and industry.

Market formation

Professor Hofbauer's impact on market formation has been limited to providing an investment opportunity for the mayor of Güssing. Two favourable exogenous factors have influenced this function: the willingness to become self-reliant in terms of energy in the town of Güssing, and the generous feed-in tariffs. As a result of political processes, the tariffs have been changed and have significantly weakened the process of *market formation*. These political processes clearly lie beyond the capacity of Professor Hofbauer's influence alone.

Legitimation

Professor Hofbauer strengthened the process of *legitimation* when he spoke in favour of the technology. However, the absence of a strategic decision by the leading capital goods supplier AE&E to promote the technology after its reconstruction presumably counteracted his influence. By recommending conventional combustion technology instead of gasification technology, AE&E probably also weakened the process of *market formation* before the change in the feed-in law. Moreover, the revised feed-in law reflects the deteriorating legitimacy of renewable fuels in general and biomass-based power production in particular.

Development of positive externalities

The main function that appears to have been strengthened through positive external economies is *knowledge diffusion*. This has been achieved in two ways. First, by being instrumental in setting up a learning network, Professor Hofbauer has facilitated the sharing and diffusion of information within Austria, as well as with parties in the EU. Second, by being involved in a continuous learning process in both Güssing and Oberwart, Professor

Hofbauer is the node through which experiences are shared between the two plants. This node is of particular importance after the disruption in the biomass gasification network following the exclusion of Repotec from the construction of the Oberwart plant.

A strong motor of the TIS

A strong motor was initiated when Professor Hofbauer managed to mobilise resources (*resource mobilisation*) from AE&E. Based on his previous knowledge in coal gasification, he managed to *materialise* the technology in the form of various pilot plants and thereby conduct the first *entrepreneurial experiments* for realising small-scale CHP production based on biomass gasification. These plants were important for advancing *knowledge development* to a stage where he felt that the technology was ready to be scaled up to a commercial-sized plant.

By making use of the general structure—in terms of the EEG (Erneubare-Energien-Gesetz), a risk absorption scheme, EU regional development funding and the interest of the town of Güssing to become independent of fossil resources—he was able to set up a network of actors with an interest to pursue the technology and the Güssing facility could be *materialised.* The Güssing plant then became a very important resource in itself, as further knowledge networks could be setup and further resources mobilised (RENET and several EU projects) for even more *entrepreneurial experiments*, strengthening *knowledge development.*

These positive interconnections between functions and structure have resulted in the materialisation of a science and technology infrastructure, carrying its own operating costs, and enabling a very rapid technology development. The actors within the TIS were able to develop the technology from laboratory-scale in 1994, and simple heat and power production at the Güssing plant in 2002 to a plant showcasing many advanced experiments and operations. The cost of operations has been reduced, efficiency has increased, advancements have been made in gas cleaning, and a BioSNG demonstration has been constructed along with pilot projects for FT diesel production, fuel cells, and so on.

By strengthening the technology structure, he also became attractive for other actors with similar interests to collaborate with (strengthening the actor structure). As a result, he could build strong knowledge networks around the plant and the plant became a collective resource in the network, enabling further *resource mobilisation*, *knowledge development*, *entrepreneurial experimentation* and *materialisation*. The strong motor is, thus, primarily based on the positive interactions between the processes of *resource mobilisation, entrepreneurial experimentation*, *materialisation* and *knowledge development and diffusion* and the structural elements of technology, actor and knowledge networks.

To conclude, Professor Hofbauer made use of the general structure by:

1) Utilising existing technology structure by drawing on coal gasification and combining it with knowledge of biomass for creating small-scale systems.
2) Mobilising resources by attracting a) incumbent capital goods manufacturer AEE through personal contacts to explore the small-scale CHP application, and b) international collaborations to develop the technology by offering a research platform.
3) Mobilising resources available due to a) the town of Güssing, being situated in an underdeveloped region and with an interest to become independent on imported resources, b) the existence of EU and Austrian regional development funds, and c) the EEG and a risk absorption scheme.

As a result, he has been able to strengthen all of the functions of the TIS, but has been particularly successful in strengthening *resource mobilisation, entrepreneurial experimentation*, *materialisation,* and *knowledge development and diffusion*. He has, furthermore, been able to add to the actor structure by attracting further actors to the field, strengthening networks by setting up various knowledge networks, strengthening the technology structure of the TIS by constructing pilot and demonstration plants, and enabling a second commercial CHP plant in Oberwart.

5.2.2 Limits of the system builders' transformative capacity, system weaknesses and the potential role of policy

Although it was previously argued that the system builder has been able to strengthen all of the functions, there are still limits to his transformative capacity. These limits have resulted in a weak motor and weak structural elements of the TIS. In this section, the limits of the system builder will be identified. The resulting system weaknesses and the potential role of system builders and policymakers for resolving these are also discussed.

Beyond the influence of Professor Hofbauer, the weak motor in the TIS started when AE&E chose to exit and focus on conventional combustion technology. AE&E, being the leading capital goods supplier in Austria, probably weakened both *market formation* and the *legitimation* of the technology by its strategic choice. The legitimacy of the technology was further weakened when the use of biomass for electricity purposes was strongly questioned and capped. The subsequent change in the feed-in law blocked *market formation* for gasified biomass and weakened the function *influence on the direction of search*.

The weak motor negatively influenced the structural development of the TIS, primarily since new Austrian actors have been discouraged from entering the TIS. Without a strong actor base, influential political networks cannot be formed. To date, mainly international partners have been attracted to join the knowledge network and—save for the customer of the second plant, BEGAS, and its constructor Ortner—there is a lack of financially solid Austrian actors that are ready to back up the technology and develop the TIS. The troublesome relationship between some key Austrian actors has also obstructed the formation of political networks. These networks are, however, essential in forming influential political coalitions that can align the necessary institutions. In the prevailing situation, where the legitimacy of biomass in electricity production has been weakened, a strong coalition is needed to address this issue and induce the required institutional alignment. Otherwise, Austria may well find itself in a position where the benefits of the encompassing knowledge development are appropriated on by other actors elsewhere in the EU. Hence:

> *The main system weakness is lack of actors and political networks with an interest in aligning the institutional framework in support of the technology.*

The Austrian government has been very active in supporting the build-up of knowledge through the competence centre RENET and other sources of funding. The system builder and the larger network of actors have also been able to access considerable amounts of EU funding for furthering knowledge and technology development. The actors that are needed to develop the technology appear to be there. Naturally, the Güssing facility is of particular importance since it provides the researchers with the necessary infrastructure for conducting further experiments, while the facility itselves carries its own operating costs. With time and continued research and development support from the EU and the national government, a breakthrough in the poly-generation of heat, electricity and BioSNG clearly appears to be possible in Austria.

Yet, despite this impressive Austrian achievement in gasified biomass, the Austrian government has obstructed the exploitation of that knowledge base. In particular, it has not implemented a market formation policy that differentiates gasification technology from conventional biomass technologies and has, thus, not provided the technology with the necessary preconditions for becoming an attractive field for new customers and suppliers. A case in point is AE&E, which could have re-entered the TIS after the reconstruction had there been a clear demand that could have balanced the huge demand for biomass usage with fluidised bed combustion.

As specified above, main structural weakness concerns the lack of necessary political networks for biomass gasification in Austria. Such a network would, for instance, push for special feed-in conditions for innovative power technologies and/or special conditions for BioSNG and biomass-to-liquid technologies. Extending the current knowledge network into a strong political network is, arguably, beyond the capacity of the system builder Professor Hofbauer; further support must come from policy.

In order to form a strong political network, some or all of the major technology suppliers (such as AE&E, Ortner and Andritz) must be included in it. Andritz is a world leader in supplying equipment to the pulp and paper industry and recently bought the Finnish firm Carbona, which has strong competencies in biomass gasification (Salo, 2008; see Chapter VIII). This acquisition is part of a movement among dominant actors in the Swedish and Finnish pulp and paper industries to integrate gasification technology at some of their sites for BtL production. With integration, the industry can benefit from additional renewable production of electricity, the production of biofuels or BioSNG, and access to process heat. Paper mills involve a vast flow of biomass resources, including residues that cannot be used in the production process. This flow of biomass can be expanded at a considerably lower cost in the mills than at a competing standalone site (see Chapter III).[125] With the integration of the Güssing technology, the Austrian pulp and paper industry may thus have the potential of adding additional streams of income.

The political network would, of course, be considerably strengthened if it included the pulp and paper industry.[126] However, up until recently, there has been little awareness of the potential for biofuel production in the industry and it is not part of the Austrian network for biomass gasification (Dworak and Zettl, 2008). Indeed, for reasons mentioned above, the industry was instrumental in altering the design of the feed-in law that blocks market formation for the technology and induces Repotec to exploit its technology abroad, together with foreign partners.[127]

The position of the pulp and paper industry in Austria is, however, probably not set in stone. Attention is now being given to this issue in the industry (Dworak and Zettl, 2008),[128] and an opening now exists for "governance on the inside" which understands policy as politics rather than management (Smith and Stirling, 2007, p. 364):

> "In 'governance on the inside', processes of engagement, dialogue and deliberation require explicit and careful attention to questions of power, authority, consent, dissent and, above all, legitimacy."

Arguably, a policy actor in such a process could seek to align the interests of the pulp and paper industry (including its equipment suppliers) with those of the emerging TIS for gasified biomass. We acknowledge that the transformative capacity of policymakers is " ... structurally constrained by historically established commitments, embodied in infrastructures, networks, institutions, practices and discourses" (Smith and Stirling, 2007, p. 355). Yet policymakers may attempt to use its constrained agency to provide incentives that

[125] There have been many studies pointing to an integrative approach as being less costly than in using standalone plants for BioSNG and BtL production cf. (Ekbom et al., 2003; Larson et al., 2003; DENA, 2006; Larson et al., 2006; McKeough and Kurkela, 2008).
[126] The pulp and paper industry is a dominant one in Austria, with an annual turnover of €3,769 million in 2007 http://www.austropapier.at/.
[127] These include Conzepte Technik Umwelt from Switzerland and the Stuttgart-based company M+W Zander FE GmbH.
[128] Indeed, Dworak (2008) suggests that biofuel will be an important issue for the industry.

enlarge the knowledge network to include the pulp and paper industry and its equipment suppliers and eventually transform it into a political network.

These incentives may be varied, but two opportunities for policymakers will be described here. First, they could take the lead in funding and designing a biorefinery[129] programme. Biorefineries are one of the key innovation issues for the European pulp and paper industry. Although pilot plants are being built in mills owned by international firms that also have plants in Austria, they are located elsewhere (such as in Finland and Sweden) and thus utilise non-Austrian competencies. An Austrian programme could form a platform for exploiting and enhancing the strong Austrian knowledge base, and for expanding the TIS network.

Enhancing the Austrian knowledge base would include strengthening the capabilities connected to fuel production. This is particularly important for AE&E, which remains prepared to re-enter the TIS as long as there is a reasonable market with clear projects. However, the core competence of AE&E lies in boilers and power plants, and not fuel production and the associated knowledge fields of catalysis and synthesis processes. As was explained in Chapter III, making transport fuel from gasified biomass involves advanced competencies that are normally found in the chemical industry; the design space has changed. As AE&E chose to delink itself from the Güssing plant and its experiments with transport fuel production, it has not participated in the knowledge formation with respect to fuel production and would, therefore, need a project partner if and when it wish to re-enter the market (Kaiser, 2008).

Second, the feed-in law would need to be revised to provide a market space for the Austrian technology, while accommodating the needs of the pulp and paper industry. Special incentives such as investment subsidies also need to be established to induce the building of demonstration plants for BtL production in the pulp and paper industry. The funding of these demonstration plants would need to be organised in a manner that either fully shifts the risks from investors and technology suppliers to society or shares the risks. Ultimately,

[129] There are many definitions of the concept of "biorefinery", but we make reference to future production sites that may co-produce liquid or gaseous transportation fuels and other advanced, high value chemicals through gasification, within conventional pulp and paper mills.

however, it is the potential members of the political network who are responsible for formulating the conditions that are necessary for making further investments.[130]

5.3 Conclusions

This chapter illustrated that an individual, in this case an academic, can take on the role of a system builder, especially in the early phase of the formation of a TIS. The transformative capacity of Professor Hofbauer was analysed by addressing his ability to, through a range of activities, strengthen a set of key innovation and diffusion processes, or functions, and the structural elements of the TIS. With time, a network of actors has taken over the system building role although Professor Hofbauer has remained influential in the TIS.

It was illustrated that the system builder managed to strengthen the structure and functions by drawing upon the general structure in which he is embedded by:

1) Utilising existing technology structures by drawing on coal gasification and combining it with knowledge of biomass for creating small-scale systems.

2) Mobilising resources by attracting a) incumbent capital goods manufacturer AEE through personal contacts to explore the small-scale CHP application, and b) international collaborations to develop the technology by offering a research platform.

3) Mobilising resources available due to a) the town of Güssing, being situated in an underdeveloped region and with an interest to become independent on imported resources, b) the existence of EU and Austrian regional development funds, and c) the EEG and a risk absorption scheme.

As a result, he was able to strengthen all functions of the TIS, but his capacity had the strongest influence on the processes of *resource mobilisation, knowledge development and diffusion, entrepreneurial experimentation*, and *materialisation*. A part of his capacity was used to overcome the frictional resistance in the form of troublesome network relationships (Repotec being delinked from the Oberwart plant). He was also able to add to the actor

[130] Timing is essential here. The TIS in other countries are currently being built up and Andritz is already tied up in an alliance with a Finnish company (Carbona) that is not very different from Repotec, as well as with a Finnish partnering pulp and paper actor (UPM).

structure by attracting further actors to the field; strengthening networks by setting up various knowledge networks; and strengthening the technology structure of the TIS by constructing pilot and demonstration plants, and by enabling a second commercial CHP plant in Oberwart. The interactions between these four functions and the structure are extensive and positive. This is, thus, a strong motor in the TIS that has, in turn, resulted in a rapid structural build-up.

The system builder has been much more limited in his ability to strengthen *influence of the direction of search*, *legitimation* and *market formation*. Indeed, these functions interact in a pattern that generates a weak motor. The motor is clearly not strong enough to attract incumbent Austrian actors to the TIS and the subsequent formation of a political network that could, in turn, be used to align the institutional framework. As a result, the Austrian-based actor structure consists of relative small firms with problems to appropriate on the knowledge development taking place.

The main system weakness is, therefore, actors and political networks with an interest in aligning the institutional framework in support of the technology.

This motor and system weakness is also exceptionally difficult for a single individual to influence, since it is driven by neglect of or by intentional resistance from powerful actors. It is shaped primarily by the dominant capital goods supplier's (AE&E) strategic decision to avoid taking initiatives in the area, and the revision of the regulatory framework (the feed-in law), which has ruined the economics of building new gasification plants in Austria. In sum, the system builder has strongly contributed to creating an opportunity for Austria, but factors beyond his influence currently obstruct the realisation of this option.

There is, however, strong external pressure on Austria from the EU to provide new incentives for actors to produce more renewable electricity and renewable transportation fuels. If Austrian policymakers identify biomass gasification as a key technology in reaching such targets, there appears to be a solid industry structure and knowledge base that can enable such an expansion. While they are currently failing in providing the technology with the necessary preconditions for becoming an attractive field for new customers and suppliers, policymakers clearly have options available to them. These options would aim to not only enhance market and knowledge formation, but also to include actors that have hitherto generated both frictional (AE&E) and intentional (the pulp and paper industry) resistance in the knowledge network, and turning it into a political network. Policymakers, therefore, need to add a strong element of system building activities that interact with and supplement those pursued by Professor Hofbauer and his network.

Germany

Chapter VI
Germany

The history of gasification in Germany has been long and closely related to the general development of knowledge in the field of gasification itself (as described in Chapter III). During the Second World War, the Nazi regime put forth great efforts into developing coal liquefaction technologies such as the Fischer-Tropsch synthesis for producing liquid transportation fuels that could replace conventional oil. When cheap oil re-entered the market after the war, the need for domestic production of coal-based transportation fuels disappeared. However, the industrial knowledge base of using coal for the production of various chemical and transportation fuels had been advanced, thereby making German industry even more capable of supplying gasification and various types of chemical plants.[131]

Today, the capital goods industry in Germany consists of firms such as Lurgi, Siemens, Uhde, Envirotherm, Lindé, Südchemi, and Reinbraun. These companies are some of the world's leading capital goods suppliers and engineering firms for chemical plants based on the gasification of fossil resources. They are capable of delivering solutions for the production of ammonia, methanol and SNG, as well as, more recently, the IGCC process for power production (Chapter III).

The development of Fischer-Tropsch liquids was taken over by the South African firm Sasol. This development work continued under the apartheid regime and large-scale commercially operating plants were launched in the 1970s. Recently, Sasol entered into a technology joint

[131] Coal gasification competencies were also further developed for the production of town gas in the former DDR. Capital goods suppliers in Germany today benefitted from the technology development at that time.

venture with Lurgi to further develop gasification and downstream technologies (Turna, 2007).[132]

The capital goods industry in Germany is highly capable with respect to coal gasification. However, their interest in developing the technology for biomass has, until recently, been relatively modest even though some experiments have taken place. For instance, to date Lurgi has developed and sold the world's largest atmospheric CFB (100MW) cement kiln gasifiers to a factory in Rudensdorf (in 1995). A second unit was sold for co-firing biomass-derived gas in a 600MW coal boiler in the Netherlands.[133] Another major engineering firm, Uhde, supplied a high temperature Winkler (HTW) reactor to the Finnish company Kemira for methanol production based on peat at the end of the 1980s (see Chapter VIII). However, neither Uhde nor Lurgi continued to develop biomass gasification as a new business based on these experiences.

It was not until more recently that three major and two minor projects were initiated with the purpose of turning various types of biomass into transportation fuels and other chemicals. Hence, the history describing the evolution of the five projects in the subsequent sections will start no earlier than the beginning of the 1990s.[134]

At the centre of each project, there is an actor performing system building activities. The role of these various actors has, naturally evolved over time in the individual cases. Nevertheless, four system builders have been identified: the start-up company Choren, and the research institutes Forschungszentrum Karlsruhe (FZK), Zentrum für Sonnenenergie-und Wasserstoff-Forschung (ZSW) and Clausthaler Umwelttechnik-Institut (CUTEC). An important

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[132] Since August 2007, Lurgi has been fully owned by the Air Liquide Group from France. Sasol-Lurgi are not the only actors with competence in FT synthesis. The Dutch company Shell has also developed the technology and used it to produce diesel from stranded natural gas fields.

[133] In 2002, Lurgi decided to sell their CFB technology used with biomass, as well as the British Gas Lurgi (BGL) fixed-bed coal technology. The BGL had previously been demonstrated at SVZ pump with coal and waste by the company Envirotherm (Hirchfelder, 2008). No new installations based on biomass have been made by Envirotherm, although there have been a few based on coal. Biomass gasification has not been ruled out by Envirotherm, but they do not see a big market in this area, as compared to coal gasification.

[134] As in Austria, there have been numerous experiments conducted at research institutes, universities, small private companies, and in people's garages on fixed-bed gasification for biomass. Most of these experiments have been geared towards very small-scale (<1MW) gasification for combined heat and power production. Some of them have resulted in the establishment of firms that have managed to install a few plants where poor operational performance has been a major issue (Bräkow and Oettel, 2008). As mentioned in Chapter IV, these experiments have been excluded from the study.

actor within fossil gasification, which also could have played a role in strengthening biomass gasification, is the University of Freiberg. However, it will be argued that it does not undertake system building activities of any particular importance.

The structure of this chapter is built around the three main system builders—Choren, FZK and ZSW. Their respective histories will be described in the first section of this chapter, while the histories of CUTEC and the University of Freiberg will be summarised in boxes. Thus, this first section focuses on describing the interactions between actors and the characteristics of the emerging technological innovation system (TIS). The focus is on how the system builders act to create the emerging structure of the TIS, both by building the structure directly and by strengthening the various functions outlined in Chapter II. Also included in the three main histories is a description of what the system builders consider to be necessary for realising their technology option on a commercial-scale.

The second section of this chapter provides answers to the research questions (as specified in Chapter II). The discussion starts with identifying who have been acting as the system builders, and describes the nature and extent of their transformative capacities. The focus then shifts to analysing and explaining the limits of the system builders' transformative capacity, identifying main system weaknesses, and discussing the potential role of system builders and policymakers in addressing these weaknesses. The third section of this chapter presents the main conclusions.

6.1 The evolution and prospects for biomass gasification in Germany

In this section, the five main projects and alliances will be presented from the perspective of the system builder of each project. The first sub-section focuses on the start-up company Choren, which has managed to create an alliance consisting of a large group of investors, technology suppliers and other stakeholders for the realisation of a concept for a two-stage gasifier for the production of FT liquids. A box in this sub-section summarises the Technical University Bergakademie Freiberg's plans for realising a modified HTW reactor. The second sub-section presents the endeavours of FZK, a technical institute that has entered into an alliance with the capital goods supplier Lurgi for the purpose of commercialising a large-scale, three-stage and distributed gasification concept. The third sub-section discusses the alliance created by institute ZSW, which works on a smaller-scale concept based on the FICFB gasifier that has been demonstrated in Güssing (Austria) with the goal of BioSNG production. A box in this sub-section summarises the efforts of a third institute, CUTEC, in commercialising a CFB gasification technology for FT diesel production.

6.1.2 The emergence of Choren Industries and the Carbo-V technology

The fall of the Berlin Wall in November 1989 paved the way for German reunification, which formally took place on October 3, 1990. Reunification resulted in a major reorientation of German society as a whole; most importantly for this story, however, it led to the dismantling of the major research institutes in the former East Germany (DDR) and the establishment of major development funds for stimulating economic growth and employment in the eastern parts of reunified Germany.

One of the dismantled institutes was the Deutscher Brennstoff Institut (German Combustion Institute), or DBI, which carried out major research on lignite, brown coal, combustion, and gasification. Lignite extraction and use was at the heart of East Germany's economy and energy supply, employing 130,000 people and accounting for approximately 70 percent of its primary energy supply (Hansen, 1996).

DBI's technical director, Bodo Wolf, had been responsible for a number of gasification projects, of which Schwarze Pumpe is the most well known. In 1969, Schwarze Pumpe was the world's largest lignite gasification plant for the production of town gas and produced 85 percent of the gas used in the former DDR (Picard, 2008b).

After reunification and the dismantling of DBI, Mr. Wolf formed the company Umwelt- und Energietechnik Freiberg (UET) GmbH, and convinced four former DBI colleagues to work with him in the new company. At the start, they performed mostly classic engineering work, but Mr. Wolf's goal was to further the extensive gasification experience they already had with lignite, and use it to produce liquid transportation fuels from biomass (Rudloff, 2008b).[135]

[135] Unfortunately, we could not arrange an interview with Mr. Wolf. As a result, we do not know why he became involved in using biomass.

From his position at DBI, he had gained extensive experience with both fixed-bed and entrained flow gasification. Based on his experience, he ruled out fixed bed and fluidised bed gasification for producing a tar-free gas that could be transformed into transportation fuels. Instead, he invented the Carbo-V process which combines the low temperature fixed bed and high temperature entrained flow gasification technologies into a continuous flow. It can, therefore, handle the physical properties of biomass (i.e., its heterogeneity and large size), while producing a clean gas using a high temperature process (Rudloff, 2008). By leveraging his experience with coal gasification he expanded the design space of fossil gasification to include biomass by redesigning the process.[136]

When Mr. Wolf presented the idea for the first time in 1995, it was not well received. No one at the time was particularly interested in the production of liquid fuels from biomass; rather, the focus was on hydrogen production (*direction of search)*. Despite this general scepticism, Mr. Wolf managed to raise the funds necessary for constructing a first pilot plant. The primary source of funding, about 60 percent, came from the state of Saxony. The remainder came from his friends and his own savings (*resource mobilisation*) (Rudloff, 2008b).[137]

In 1997, UET changed its name to Choren[138] to reflect the new direction that the company was taking. With the funding Mr. Wolf received, a pilot plant could be constructed (*materialisation*) and it was completed by 1998. It became the first *entrepreneurial experiment* based on the Carbo-V process. The pilot plant was able to gasify 250kg of biomass per hour, equivalent to approximately 1MW.

Three elements of the structure at the end of the 1980s and beginning of the 1990s, created the necessary preconditions for Mr. Wolf to develop its own technology construct the first pilot plant. First, DBI and Schwarze Pumpe (SVP) permitted Mr. Wolf and his co-workers at Choren to draw on the technology already developed and tested. Second, the dismantling of the institute and ongoing downsizing of SVP (which was finally shut-down in 2008) had

[136] In the Carbo-V concept, biomass can be co-gasified with coal if desired.
[137] Ample funding from the federal government (through the state of Saxony) was available for technology start-ups such as UET in the eastern part of Germany through a special development fund (Rudloff, 2008b).
[138] C-Carbon, H-hydrogen, O-Oxygen, REN-Renewable (Bienert, 2007).

provided Choren with excellent opportunities for hiring experienced personnel who continue to be an important resource for the company. Third, the availability of funding through the East German development funds enabled the system builder to mobilise financial resources.

These resources made it possible for the system builder to further advance *knowledge development* and *entrepreneurial experimentation,* which eventually resulted in the *materialisation* of a first pilot plant. In addition, Mr. Wolf and the first employees of Choren were driven by a vision: with the completion of the pilot plant, they managed to strengthen the *direction of search* for liquid synthetic fuels, for which there had been no apparent demand.

Finding partners and scaling up plans, 1998–2008

Following plant construction between 1998 and 2001, the pilot plant was optimised for gas production and numerous tests were conducted using different types of fuels to improve the overall process (*entrepreneurial experimentation* and *knowledge development*). With the pilot plant completed and several patents granted on process, the technical uncertainties of the new concept were reduced and the legitimacy of the process—and of Choren as a company—was increased (*legitimation*). Hence, favourable conditions for finding additional partners had been created.

Mr. Wolf realised early on that strong partners would be critical to his company's success. He firmly believed that a small technology company could not manage to build and market large-scale gasification systems by itself (Rudloff, 2005, 2008b). By chance, he came into contact with some key individuals that could help him take the next steps towards realising his biomass gasification concept.

One of these individuals was Dr. Hanns Arnt Vogels, who was a member of the board for the vehicle manufacture Daimler and the director of the board for the Swedish-German joint venture Vasa Energy GmbH in Hamburg. At the time, Vasa Energy was owned (50 percent) by Michael Saalfeld, whom Mr. Vogels knew very well. Mr. Wolf was introduced to Mr. Saalfeld and, when Mr. Saalfeld later sold his shares in Vasa to Vattenfall, he invested some of the money in Choren and became its lead investor. In 2003, he followed up on this investment by bringing in nine other private investors from within and around the Hamburg area (*resource mobilisation*) (Rudloff, 2008b).[139]

It was probably due to their contacts with Dr. Vogels that, shortly thereafter, Choren was awarded a project with Daimler to produce methanol for fuel cells (since that was the primary interest of Daimler at the time). However, Daimler was not the only German automobile manufacture with an interest in alternative fuels. Their main competitor in Germany, Volkswagen (VW), had created a new department for biofuels and appointed Dr. Wolfgang Steiger to lead it. This organisation had been investigating different alternative biofuel options and had already been in contact with Choren between 1996 and 1998 (Seyfried, 2008a).

Due largely to the persistent work of Dr. Steiger, BtL was put on Volkswagen's agenda and a cooperation agreement was signed between Daimler, VW and Choren in 2002. The goal of this project was to promote BtL fuel and, for Choren, to supply synthetic fuels for motor tests at the two companies (Seyfried, 2008a). All three companies strongly felt that a common strategy for the promotion of BtL would be important and of mutual interest, even if VW and Daimler otherwise view each other as competitors.

Cooperation was possible since Daimler and VW had no interest in becoming fuel suppliers but did have an interest in achieving a common fuel standard. They both preferred FT diesel over other renewable alternatives, since it is considered to be "infrastructure ready" and can be blended with ordinary diesel at any quantity without any engine modifications. It even enables cleaner and more efficient combustion compared to conventional diesel. By collaborating with Choren, they were able to influence the fuel quality resulting from the process (Drescher, 2008; Seyfried, 2008a).[140]

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[139] http://www.lichtblick.de/lichtblick/unternehmen.php?lbid=7DrybjEEUKJv&v=4&&s=2 Accessed 2008-05-20

[140] Both VW and Daimler have been working with all types of fuels available on the market. They do, however, prefer a moderate level of blending (5-10%) in the diesel from first-generation biodiesel, since it has been considered to have inferior fuel properties. Natural gas has a high cetane number (i.e., a high combustion quality) and is possible to use in some models. It has also been considered as an inferior option since it has a considerably lower energy density, it is not infrastructure ready, and it is not a diesel fuel. Similar arguments have been used against dimethyl ether, promoted by various actors in Sweden (Chapter VII), which is a diesel

Thus, Choren, offered hope (*direction of search*) of creating a renewable fuel alternative, which would be infrastructure ready and could be blended at any quantity with conventional fuel. It was thus comparable, or even superior, to fossil alternatives and much preferred over an increased blending of first-generation diesel fuels from food crops. The promise of Choren's technology made them an attractive partner to collaborate with. In addition, the involvement of the two major automobile manufacturers in Germany strengthened the TIS, and the collaboration granted Choren new and considerably increased legitimacy (*legitimation*).

At this point, with the backing of its partners, Choren was ready to apply for more money from the government. It applied for approximately €4.6 million from the Ministry of Trade and Economics to construct a methanol and Fischer-Tropsch synthesis unit. The application was granted and the new equipment was installed at the pilot plant (*resource mobilisation, materialisation*) (Rudloff, 2008b). The first methanol was manufactured in April 2003 and the first FT product in June of the same year (*entrepreneurial experimentation, knowledge development*). With this new equipment, the entire production process, from biomass-to-liquid production, could be demonstrated, as could the quality of the fuel itself (Baitz et al., 2004; Rudloff, 2005, 2008b). This was of course a very important step for Choren. However, the scale of the pilot was too small to prove the viability of the process, and a larger demonstration plant had to be constructed to further reduce technical uncertainties.

The demonstration plant

The general idea of the new plant was to demonstrate the stand-alone and continuous production of FT liquids. It would have to be done on a scale that was large enough to reduce the technical risk to an acceptable level for potential customers and investors in future commercial-scale plants. Commercial size was estimated to be an annual production rate of 200,000 tonnes of liquid fuel (Bienert, 2007).[141]

To reduce the risk to a reasonable level it was therefore judged that the demonstration should be in the range of 45MW_{th}, consuming 65,000 tonnes of dried biomass and being able

fuel but has a lower energy density and is also not infrastructure ready (Keppeler, 2007; Drescher, 2008; Picard, 2008a; Seyfried, 2008a).

[141] Such a plant would require about 1 million tonnes of biomass annually, and the gasification units in this plant would have to have a combined capacity of approximately 700MW (Bienert, 2007).

to produce 18 million litres of FT diesel annually. The plant would be based on the same two-stage gasification concept as the pilot plant and constructed in Freiberg, next to the pilot plant. Even if liquid production in the demonstration plant would be considerably more expensive than in a commercial-scale plant, it was thought to have a commercial value (Rudloff, 2008b).

The two main challenges in constructing a demonstration plant were a) raising more than €100 million and b) finding a partner that could supply the FT synthesis unit at the required scale.[142] The key to raising €100 million was identified as finding a customer that could agree to leaving an "offtake guarantee"[143] on the demonstration plant's future production. The guarantee was seen as necessary to reduce the market and financial risks for investors and offer some return on the project (Rudloff 2008).

The first steps in financing the project had already been taken when Choren was granted €4.6 million from the Ministry of Trade and Economics in 2002, allowing the construction of the first components of the plant. However, at least €95.5 million of the required funds still had to be raised.

In January 2004, the 6th EU Framework Programme, RENEW, was initiated with Volkswagen as the coordinator. A network was set up with 32 partners from nine countries. The programme ran for 48 months and had a budget of €19.8 million (€10 million in EU funding and €10 million in partnership funding), of which Choren was allocated about €5 million[144] (*resource mobilisation*) (RENEW, 2008; Seyfried, 2008b).[145]

The benefits provided by the RENEW project were much more than financial. First, and perhaps foremost, it contributed to strengthening the *legitimation* of the entire knowledge field. It did so by demonstrating that a significant share of the diesel being consumed in EU-

[142] FT units are normally built on a much larger scale, and developing the technology on their own was judged to be impossible (Rudloff, 2008b).
[143] An offtake guarantee, or offtake agreement, is a purchasing agreement between a buyer and a supplier on the price and volumes of the future production. These agreements are made prior to construction and make it easier to obtain financing for the construction, but they are usually difficult to obtain when dealing with non-commercial technologies.
[144] €2.5 from the EU and €2.5 was equity financing (Choren, 2010).
[145] Without the solid connections to VW, it was judged unlikely that the allocation of funds to Choren would have been as significant (Rudloff, 2008b).

27 could be substituted by liquids produced from domestically grown biomass at a cost of approximately €1/litre diesel equivalent, depending on which technology was used.

Second, the project considerably strengthened the legitimacy of Choren as a company. The RENEW project examined seven different gasification technological trajectories; only two of them, however, including one from Choren, were considered ready for large-scale demonstration (RENEW, 2008). Third, the study illustrated that the Choren process was the most cost competitive and energy efficient solution among the German trajectories, which was especially important for Choren vis-à-vis their main German competitor FZK/Lurgi. Among the six participating trajectories, only the Swedish company Chemrec showed better results than Choren.[146]

The major step for securing the remaining and required funding for the demonstration plant was taken when Shell became involved in the project. Choren's Mr. Rudloff (2008b) described that he was under the impression that the intention of Volkswagen from the start was to bring them into partnership with a major oil company. After 18 months of negotiations with both BP and Shell, an agreement was reached with Shell and a contract was signed in August 2005 (Shell, 2005; Rudloff, 2008b).

According to the agreement, Shell would buy 25 percent of Choren shares, provide their FT technology and know-how in support of the construction of the demonstration plant and commit to a long-term, offtake contract for the entire production from the demonstration plant. The offtake guarantee was, thus, a key part of reducing the financial and market risks for other investors, and making investing more attractive for them (Rudloff, 2008).

The legitimacy of biomass gasification in general and Choren in particular was boosted by Shell's entry into the TIS. Shell was expected to reduce the technical risk of the project by supplying their FT technology and know-how from fossil gasification.[147] Shell's entry also further increased the financial, human and complementary technical resources (*resource*

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[146] Chemrec, however, focuses on DME production and not diesel, which is not a preferred transportation fuel according to Volkswagen and Daimler (Keppeler, 2007; Seyfried, 2008a). It is also important to observe that the potential Finnish FT-liquid production plants were not included in the study. Based on preliminary calculations made by VTT, they show similar performance to Chemrec and, thus, a significantly lower cost level than any of the German development tracks (McKeough and Kurkela, 2008).

[147] Shell is one of only two companies that has commercially operating FT technology (Chapter III).

mobilisation). All these factors played an important role for raising the remaining funds for the construction of the demonstration plant.

Choren was thus able to secure a total €25 million with loan guarantees through KfW Bankengruppe[148], a Federal- and Länder-owned financial organisation (*resource mobilisation*). The loan guarantees were granted to the lending banks and they can cover up to 80 percent of the total debt financing. The guarantees were seen as a critical success factor for the project since no external power contractor (EPC) would have been willing to supply the demonstration plant for at a fixed price and with guarantees concerning its operation (since the technology had not been proven). Without such guarantees from an EPC, or the guarantees provided by the KfW, ordinary banks would not have been expected to grant Choren a loan for the demonstration plant, regardless of the agreement with Shell (Rudloff, 2008).

Plant construction was initiated in 2005, and further financial resources were mobilised in 2007 when Volkswagen and Daimler decided to buy a minority share of Choren (Choren, 2007a). The mechanical completion of the plant took place in April 2008. Following inauguration, however, Choren estimated that it would take 8 to 12 months to begin the individual plant sub-systems before any BtL could be produced (Choren, 2008). For various reasons, start-up has been further delayed and as of November 2009, no diesel had yet been produced at the plant.[149] In addition, Shell has since decided to sell their shares in Choren (Choren, 2009). It is too early to say what this ultimately means.

In sum, the very capable system builder Choren and its founder Bodo Wolf have demonstrated a capacity to considerably strengthen the functions of *knowledge development, entrepreneurial experimentation*, *materialisation*, *resource mobilisation, direction of search* and *legitimation*. This has been achieved by successfully building a first

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[148] KfW Bankengruppe is a public organisation that is 80 percent owned by the federal government and 20 percent by the Länder. http://www.kfw.de/. Loan guarantees are specific instruments available in Germany and Austria but not in Sweden and Finland.

[149] In the demonstration plant, the entire production chain, from biomass-to-liquids, is integrated in a new way and on a scale that has never before been attempted. It involves the start-up of several hundred different sub-systems that have never been operated in combination before. It is expected to take time before everything works properly. One can, for example, compare this with the Värnamo plant, which has a considerably simpler process than liquid production from biomass. Still, it took approximately three years before the plant had accumulated 600 operating hours (Chapter VII).

pilot plant and creating strong alliances with leading firms from the automotive and petro-chemical industries.

However, the continuous production of FT diesel on the scale of a demonstration plant remains to be proven. In order to succeed, it will probably be necessary to further strengthen *knowledge development* and to mobilise additional capital to operationalise the process (further *resource mobilisation*). If the demonstration can be made operational, Choren would significantly strengthen the function of *market formation.* If it fails, it risks weakening the legitimacy of the entire knowledge field.

The future of the Choren technology

If the demonstration is successful, yet another and perhaps even greater challenge lays ahead: creating the preconditions and raising the funds for the first commercial-scale plant. An investment of approximately €800 million must be made in order to realise the vision of a first full-scale plant with a capacity of producing 200,000 tonnes of FT diesel annually.

The planning and preparation of such a plant is well advanced, even if the first results from the demonstration plant have not yet been obtained. If constructed, the plant would be located in Schwedt in northeast Germany, which borders on Poland (Kiener, 2008). Choren believes that equity could provide approximately 40 percent of the capital for such a plant and that they would therefore need to raise about €480 million. The amount needed will be much higher than the current limits for loan guarantees. Direct subsidies will probably play a role but strict EU regulations control the amounts allowed. Even with the best East German subsidies, Choren estimates that direct subsidies from the current funds would take care of a maximum 10-12 percent of the entire investment (Rudloff, 2008b).

Choren's business plan includes constructing and operating the first large commercial-scale gasification plant, even if the latter is not their long-term strategic goal. With this type of plant, Choren argues that there will be great *organisational* uncertainties around who the first customers will be. Owning and operating this type of plant will be perceived as risky for these first customers, even after successful demonstrations. By taking ownership and responsibility for operating the first large-scale plant, Choren will reduce the risk for subsequent customers. This would also buy some time for potential customers to determine whether these types of plants can become a part of their current business. This could be important since there are several potential sectors (i.e., chemical, mineral oil and pulp and paper) with which the technology would relate to current competencies, even if the firms are not currently involved in fuel production or the handling of biomass (Rudloff, 2008b).[150]

For the commercial plant to become a reality, Choren will depend on the general framework in Germany and the EU to provide stable and sufficient financial conditions for the investor. The agreement between Shell and Choren, in which Shell provides an off-take guarantee, may not be possible to replicate for a large-scale, semi-commercial plant. The volumes in such a plant would be too large and without a general framework, one cannot expect that the market risk would be absorbed (Rudloff, 2008b).

Within the current legislative framework, we cannot, therefore, expect to see any investments in a commercial-scale plant, even if the technology is successfully demonstrated. This problem was raised at the inauguration of the demonstration plant by the former CEO of Choren, Tom Blades:

"The statutory framework created for first-generation biofuels has only been defined until 2015, which is not long enough for investors to plan for the first sigma plant with any certainty [...] Nevertheless, we are very confident that the politicians will shortly introduce economic policy framework enabling second-generation biofuels, and thus the synthetic biofuel made by Choren, to be a key contributor towards achieving the ambitious climate targets of the future." (Choren, 2008).

Finding a solution whereby both first-generation fuels and more expensive but perhaps also more socially desirable second-generation fuels can compete on an "equal" basis will not be easy (see Chapter XI for a longer discussion). However, Choren has advocated a separate, mandatory blending requirement for second-generation fuels, starting in 2016. According to Choren (Choren, 2007b),[151] incorporating its suggestion would help avoid competition

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[150] As of today, however, there are quite a few actors that have declared significant interest in the Choren technology. For example, the Finnish utility and biofuel suppliers Vapo and the Norwegian pulp and paper manufacture Norske Skog have expressed an interest once the technology is demonstrated.

[151] Choren emphasises that the current proposal from the German government on a revised biofuel blending law: "biofuel blending obligation for mineral oil companies", starting in 2015 will be insufficient to meet the demands from investors for a commercial-scale plant. The German proposal follows the same logic as the current EU proposal on the promotion of the use of energy from renewable sources (2008/0016 (COD)), where the CO_2 reduction potential should be the basis for how much biofuels will be necessary to blend with

between second- and first-generation fuels, and could provide a reasonably stable framework that would support long-term investments in large-scale plants.

conventional transportation fuels. The main objection against the proposed framework has been that the second-generation fuels (BtL) will compete directly with first-generation fuels.

Box 6.1: Coal and biomass gasification at the Technical University Bergakademie Freiberg[152]

During the time of the DDR, the Technical University (TU) of Freiberg developed a prominent position for its research on the thermal conversion of coal. Together with the Deutscher Brennstoff Institut (DBI) and Schwarze Pumpe (SVP), they were one of the core actors for developing energy technologies for utilising brown coal. Of the three actors, DBI focused on managing and developing larger projects including process development, while TU Freiberg focused on solving isolated problems and understanding the basic science. TU Freiberg and DBI could test, experiment and install the new processes on an industrial-scale at SVP. Hence, one can see the three actors as the pillars of a local cluster in which the interaction between the functions of *knowledge development*, *entrepreneurial experimentation*, *materialisation* and *market formation* formed a strong motor and strengthened the technology structure for the utilisation of brown coal.

When DBI was dismantled, TU Freiberg kept its scientific role but did so in the larger context of innovation in Germany and the rest of the world. Based on extensive industry collaboration in combination with the additional funding available for universities in the former DDR, TU Freiberg has become one of the top universities in the world for research on the thermal conversion of brown coal. As a result, it has been able to equip its laboratories with the latest and most advanced science and technology infrastructure, and recruit a highly reputable staff and talented engineering students. This has made it even more attractive as a scientific partner to industry.

Only 30-40 students out of a population of nearly 5,000 graduate every year with some special training in the thermal conversion of biomass. The faculty has argued that biomass conversion is interesting from a scientific point of view, but that there is very little demand from industry for students with such a specialisation. Consequently, there has also been little research on the utilisation of biomass until more recently. In 2000, TU Freiberg initiated a project along with their industrial partners to further develop the pressurised High Temperature Winkler (HTW) for biomass gasification. The HTW is a fluidised bed gasifier that was developed in the 1920s for atmospheric coal gasification. It has since been modified for higher pressures (30 bars) and temperatures. TU Freiberg developed a modified and patented reactor design. The "new" PHTW was expected to produce an almost tar-free gas from biomass in a reactor well suited for the heterogeneous character and physical properties of biomass.

Plans were also made to build a large-scale (10MW) pilot plant near the campus, as well as a facility for oxygen production. It was argued that the pilot had to be at least $10MW_{th}$, otherwise the thermodynamics of the process would change in a subsequent scale-up of the technology. This is, of course, a valid argument, but given the high cost of constructing this plant and in conducting tests and experiments, industry partners have not been willing to contribute sufficient financing. Hence, the project is arguably insufficiently aligned with the interests of TU Freiberg's industry partners. They are mainly interested in coal gasification and not in biomass. The interest of the incumbents can eventually change and the project may still be realised in the future. However, at the current levels of demand for coal gasification, this does not seem likely in the near future. With regard to TU Freiberg, they did not act (or were unable to act) to align the technology to the interests of others. Therefore, it is argued that they do not fulfil the necessary requirements, as outlined in Chapter II, for being defined as "system builders".

[152] The analysis outlined here is based on an interview with Krazack and Brüggemann (2008), as well as a five-day visit to the university when several informal interviews were conducted in 2007.

6.1.2 Forschungszentrum Karlsruhe and the development of the Bioliq process

Since Choren started its activities at the beginning of the 1990s, a competing alliance has been formed by the Forschungszentrum Karlsruhe (FZK) institute in Baden-Wuerttemberg.

The institute was founded by the West German federal government and the state of Baden-Wuerttemberg, and has since become one of the largest research institutes in Germany.[153] Until the end of the 1980s, FZK was a major institute for nuclear research and nuclear waste reprocessing. When Germany's nuclear programmes were dismantled, FZK began searching for new areas of research and started restructuring its entire operation (FZK, 2004). In 1996, as part of this restructuring and to strengthen its competencies in the field of chemistry, FZK recruited Professor Eckhard Dinjus into its Institute for Technical Chemistry, in the Division of Chemical-Physical Processing (ITC-CPV) (Dinjus, 2007).[154]

The search process was influenced by several factors (*direction of search*). Since Baden-Württemberg is one of the owners of FZK, the institute is expected to contribute to the development of industry within the state. With the experience they had in pyrolysis, and since Baden-Württemberg is a strong agricultural region, they began to consider what could be done with farm residues in a way that could increase the added value of the agricultural industry (Dinjus, 2007). According to Professor Dinjus (2007), they approached the challenge with two basic questions. First, what could be done with all the agriculture residues? Second, how would it be possible to use these residues in an industrial process at the scale of a refinery?

Straw is a residue from agriculture with little or no economic value to farmers and is generated in large volumes. The total volume of surplus cereal straw in the world has been

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[153] In total, they employ 3,800 people and have an annual budget of approximately €294 million (FZK, 2004).

[154] Professor Dinjus obtained his doctorate degree in 1973 from the Institute of Inorganic Chemistry at the Friedrich-Schiller-University in Jena. In 1996, he was appointed Professor at the Institute of Technical Chemistry at the University of Heidelberg. When he started his work at the FZK, he found little work relating to chemistry. Twelve years later, the institution is well grounded in the field of technical chemistry and respected all over the world for its scientific and applied research (Dinjus, 2007).

estimated to be approximately 1Gt/a, which corresponds to approximately 5 percent of the world's primary energy consumption (Henrich et al., 2007).

From the perspective of the FZK researchers, there are two main problems with using straw in an industrial process for green chemistry and producing transportation fuels. First, it has an energy density of approximately 1.5GJ/m3, which is low and makes it costly to transport over long distances. Second, it has high contents of ash, hydrochlorides (HCL) and K-salts such as KCL and KOH, which cause downstream problems due to poisoning of catalysts and the sticking and plugging of technical components during thermo-chemical processes (Dahmen et al., 2007; Henrich et al., 2007). According to Professor Dinjus (2007), the carbon content of the feed-stock is best converted in an entrained flow gasifier into a syngas that can be used for green chemistry and producing transportation fuels (*direction of search*). However, the physical properties and low energy density of straw make it unusable in such a reactor.

FZK researchers identified a possible solution to these problems based on the process of fast pyrolysis. Using fast pyrolysis, it appeared possible to produce a liquid with 10-15 times more energy density than straw. Although the chemical compositions would vary with the type of feed-stock used and would be highly corrosive, the liquid would resemble oil in its physical properties and would be easy to transport, pump and pressurise in an EF reactor that also could withstand its corrosive properties.

Consequently, they evaluated different existing pyrolysis technologies and concluded that the Lurgi-Ruhrgas screw reactor was the best option available and that it could be adopted for making the liquid (Dinjus, 2007). Based on the original design of the Lurgi-Ruhrgas screw reactor,[155] they developed a small laboratory-scale plant for producing the first pyrolysis slurry (*materialisation*). The pilot plant has a maximum capacity of 20kg of straw chops, sawdust, paper, cardboard pieces, etc. per hour (Dinjus, 2007; Henrich et al., 2007).

From the beginning, FZK intended to form an alliance with companies that have the capacity to bring this technology to market. By changing the properties of farm residues to something

[155] The reactor was developed during the 1950s for producing raw gas.

resembling oil in its physical properties, they also increased the attractiveness of biomass and, thereby, the possibilities of engaging the petrochemical industry (*legitimation*).

In sum, the crisis at FZK gave the researchers a reason to begin looking for more valuable areas to work in. It also provided the initial funding and motivated the recruitment of new personnel with a different competence profile than before. It thus strengthened the *direction of search* and *resource mobilisation* of the TIS. The actors could draw further resources from the structure and their work clearly strengthened *knowledge development* and *entrepreneurial experimentation*, which resulted in the *materialisation* of a pilot plant.

Finding a partner and demonstrating the concept

When the pilot plant was working and the first pyrolysis oil was being produced, FZK researchers began looking for interested partners. They could not, however, partner with a company using an entrained flow reactor. The liquid produced from straw is considerably more corrosive than conventional oil and conventional hard coal, and thus a reactor developed for those purposes would not suffice. Rather, a suitable reactor design would have to be based on low-grade coal and lignite, which had been used in the former DDR and shared the corrosive properties of pyrolysis oil (Dinjus, 2007).

The GSP reactor—the same type of gasifier that Choren based their design on—was seen as the ideal type of EF reactor. It had been developed by the former Deutscher Brennstoff Institut, which specialised in coal gasification. The GSP had also been demonstrated and been in commercial operation at Schwarze Pumpe for more than 20 years (Henrich et al., 2007; Metz, 2008). It had been developed to withstand the corrosive, salty lignite of east and central Germany and could, therefore, be expected to be capable of gasifying the oil made from straw (Henrich et al., 2007).

Hence, FZK researchers contacted the DBI gasification centre in Freiberg (Dinjus, 2007).[156] At the time, the centre was owned by Babcock. However, following its subsequent bankruptcy

[156] The Noell company took over the testing centre after DBI was dismantled, and in 1996 they erected a new 5MW GSP pilot plant at the site in Freiberg (Metz, 2008; Henrich et al., 2007).

in 2002, Future Energy GmbH acquired the technical gasification know-how from the Babcock group, including the demonstration units.[157]

In 2001–2002, FZK commenced sending samples of the pyrolysis slurry to Future Energy for testing in the GSP gasifier. In total, 40 tonnes of different bioslurries were tested (Henrich et al., 2007). A fruitful cooperation between Future Energy and FZK appears to have been established while the test campaigns progressed. According to Professor Dinjus (2007), Future Energy would have liked to continue cooperating with FZK to develop the business, based on the positive experiences they had from the different test campaigns.

However, Future Energy was struggling at the time. They had a difficult time finding contracts, since a small company with only 25 employees was not well positioned to take on large-scale contracts worth several hundred million Euros (Friess, 2008). The owner of Future Energy, Sustec Industries, was a venture capitalist based in Switzerland; since the acquisition of Future Energy, Sustec had worked to increase the attractiveness of the company as much as possible in order to find new owners. Consequently, in October 2005 Sustec also acquired Schwarze Pumpe (SVZ) in order to access the key reference plant where the GSP gasifier had previously been operating.[158] Based on the reference plant (the GSP), the experience of Future Energy and the financial resources of the venture capital firm, they managed to book a few contracts in China for coal gasification (Friess, 2008).

The new arrangement for Future Energy made them very interesting for potential buyers (Friess, 2008). In 2006, Sustec Industries sold Future Energy−including the contracts for coal gasification−to Siemens. The new owner had the financial muscle, infrastructure and other resources to continue to develop coal gasification. Since the acquisition, the business has grown considerably for Siemens: between 2006 and 2008, they increased staff from 25 to 70 and have worked exclusively with large-scale projects in China and the United States on coal gasification, for which the gasifier was originally designed (Metz, 2008).

With new owners and a booming coal gasification business, Future Energy and Siemens' interest in advancing the cooperation on biomass-to-liquid came to a halt. While Siemens,

[157] DGMK-Fachbereichstagung "Energetische Nutzung von Biomassen" vom 19. bis 21. April 2004
[158] http://www.tecpol.de/en/archive/news/05_09_29svz_selling.html accessed 2009-08-19.

recognised the positive experience they had with bioslurry and the technology's potential, with limited resource at hand biomass gasification was considered, from a business perspective, less attractive than coal. A business for biomass gasification would have to be completely driven by policy and the market would have to be created by instruments which, as of yet, are not in place (Metz, 2008).[159]

Hence, FZK was forced to start looking for other partners. Despite this, the cooperation with Future Energy has allowed FZK to advance *knowledge development* and strengthen *entrepreneurial experimentation* by attracting Future Energy into the TIS. FZK was thus able to draw on existing infrastructure, knowledge and other resources in the coal gasification industry (*resource mobilisation*). Consequently, it also strengthened the *legitimation* of the field, since it managed to illustrate the opportunities of bioslurry and convince at least one incumbent actor in the coal industry that it was a legitimate future business (at least for a limited period of time). However, when the conventional business began to do well, it was deselected by the incumbent firm since the institutional and market uncertainties were considered to be too large.

In search of a new partner

Although the partnership with Siemens never worked out, FZK still believed in the bioslurry concept and began looking for a new partner. However, finding one proved quite difficult. Not only were there very few capital goods suppliers in Germany with the required knowledge, but none would have access to a gasifier similar to the GSP. Nevertheless, both Uhde and Lurgi were considered as having interesting technology portfolios, as well as the knowledge and necessary resources to develop the entire chain of technologies needed for realising bioslurry gasification based on straw.

At Uhde, the question came up for discussion at the board of directors. Among the alternatives they had seen, the board considered the FZK solution to be the best possible

[159] Metz (2008) also refers to the impossible conditions that FZK had set in place, which created barriers to cooperation. FZK wanted a new GSP demonstration unit to be constructed in Karlsruhe, which was something Siemens could absolutely not agree with, since the plant itself contained a lot of their "know-how". Siemens also felt that it was not the gasification part that needed to be demonstrated but rather their fast pyrolysis concept on a larger scale. Siemens was unsure about sharing the risk of a large-scale demonstration plant since the process of fast pyrolysis is still uncertain at such a scale.

one for converting biomass into chemicals. However, as had been the case with Siemens, Uhde was unable to identify any customers that would be ready to invest in such plants. They also estimated that the resources required to develop the market would be too large, and they eventually declined the request to cooperate (Abraham, 2008).

Lurgi, however, was more interested in the technology than Uhde and Siemens. In August 2006, FZK and Lurgi reached an agreement for developing and demonstrating the entire concept, in which Lurgi would enjoy the exclusive rights to the technology and all future developments (Dinjus, 2007).

The reason for Lurgi's attraction to the TIS for cooperating with FZK on developing the bioslurry technology can be found in a broader set of circumstances. For some time, Lurgi had been a turnkey supplier of plants for the production of first-generation diesel and ethanol. Therefore, it could be expected to have a better understanding of the biofuel market than Siemens and Uhde. Based on its own market studies, it did not expect first-generation technologies to be sufficient in the future. For meeting goals of renewable transportation fuels within the EU and in many other countries around the world, Lurgi believed that there would be a demand for more flexible and efficient biomass-based technologies (Berger, 2008).

Bioslurry is thus considered by Lurgi to be an attractive alternative to producing large quantities of renewable transportation fuels and other chemicals from agricultural residues that would otherwise have few alternative uses. Lurgi also recognised that there will be a shortage of carbon sources in the future and increasing competition over natural gas, coal and oil resources. Biomass and straw have been identified as a valuable source of carbon which, before the bioslurry concept, would have been difficult to handle for the conventional petrochemical industry (*direction of search* and *legitimation*).[160]

The bioslurry concept also fits well into Lurgi's general strategy. Its intention is to be able to convert all carbon sources (natural gas, oil, coal, and biomass) into chemicals and

[160]It has furthermore been argued that biomass would best be used to produce chemicals and transportations fuels and not electricity or heat, since that will be the only renewable carbon source available for this sector (*direction of search*) (Dinjus 2007; Berger 2008).

transportation fuels along a technologically similar route. Since bioslurry resembles oil in its viscosity and lignite in its corrosive character, it would be able to fit right into the technology portfolio consisting of conventional, fossil-based conversion technologies.

Following the decision to cooperate with FZK, Lurgi announced that its strategic goal would be to own the complete technology chain for the production of BtL and that it would work with all feed-stocks (coal, natural gas, slurry, and biomass). Furthermore, it would give the same attention to all feed-stocks even though biomass is at an earlier stage than the other technologies (Plass, 2007; Berger, 2008). With this arrangement, the need for FZK to undertake system building activities decreases over time and the responsibility of realising the entire technology chain gradually shifts over to the alliance with Lurgi.

However, in order to take the next step towards realising a market for bioslurry and the production of chemicals and transportation fuels, the actors had to demonstrate the entire technology chain and not just the process of fast pyrolysis. The demonstration of the chain can be broken down in four distinct parts.

First, the pyrolysis process must be demonstrated on a larger scale than with the current pilot. Consequently, FZK and Lurgi constructed a demonstration plant on the scale of 5MW, or 500kg per hour of non-woody biomass at the FZK facilities in Karlsruhe. The construction of the demonstration plant was completed in June 2007 (FZK, 2007) and initial test runs were conducted at the end of 2008 (*knowledge development*, *entrepreneurial experimentation* and *materialisation*) (Dinjus, 2009). The financial resources to construct the plant were largely mobilised by FZK from the Ministry of Agriculture and Fachagentur Nachwachsende Rohstoffe (FNR) (*resource mobilisation*). FNR has strong agricultural interests and has identified the technology as having the potential to add income streams for farmers, and has therefore been supportive of the project (Dinjus, 2007). The total cost of constructing the demonstration plant was estimated in a Lurgi press release (2006) to be €3.75 million. The original plan was to be able to offer the pyrolysis units on a commercial-scale from January 2008 onwards, marketed under the name "Bioliq" (Zwiefelhofer, 2007; Berger, 2008). However, a combination of technical and non-technical problems have delayed these plans (Dinjus, 2009).

Second, a new multi-purpose gasifier (MPG) similar to the Siemens GSP is being developed. According to Professor Dinjus (2007), the patents for the GSP have expired and similar solutions could be developed with a protective screen, or a "cooling screen".[161] The development of the new MPG reactor commenced in September 2007 and the original intention was to bring it to market by December 2009 (Zwiefelhofer, 2007), although this date has since been postponed.[162] The new reactor will be designed so that it can be used for other fuels besides bioslurries, such as lignite, for which Lurgi did not have a technical solution.

Third, the gas treatment equipment has to be tested. It will be a more or less off-the-shelf technology and is not associated with any major development costs. However, the equipment needs to be demonstrated together with the other pieces of equipment (Berger, 2008).

Fourth, a methanol-to-synfuel (MtS) unit will be demonstrated. Instead of going to FT diesel, FZK and Lurgi have decided to undertake methanol production and, as a second step, convert the methanol to gasoline and diesel.[163] The MtS process will be developed together with Südchemie and Volkswagen, and the pilot will be constructed in Wolfsburg (where Volkswagen headquarters is located). Volkswagen will also perform the motor tests, while Südchemie will be responsible for the testing and development of catalysts. The total cost of the project has not been revealed but FNR has contributed €4.5 million (FNR, 2008). The demonstration was scheduled for completion by December 2009 and was to be made available to the market afterwards (Zwiefelhofer, 2007; Berger, 2008), but since this fourth step depended on the success of the previous three, the completion date of the demonstration will be considerably later than first announced. The motor test series are not expected to be finalised until 2011 (FNR, 2008). The complete chain is indeed unlikely to be demonstrated before 2012–2013, even if no major technical problems are encountered

[161] Without a cooling screen, the corrosive character of the pyrolysis oil will ruin the gasifier in less than six months, versus extending its lifetime beyond 10 years (Schingnitz and Mehlhose, 2005; Dinjus, 2007).
[162] The cost of this second step has not been revealed nor has the level of support from any third partner. Lurgi has, however, good reasons to consider the development of the MPG as a key technology and does not require any third-party financing.
[163] The process is similar to the methanol to propylene process that is used in the plastics industry, but it still needs to be demonstrated.

along the way. Given such a long time frame, these plans are very uncertain and are bound to change.

The total cost of the demonstration has not been made public, but Dr. Berger (2008) describes it as several tens of millions of Euros. However, the risks that Lurgi is exposed to will be relatively small—only the bioslurry demonstration specific to the demonstration of biomass-to-liquids is exposed, and this will largely be paid for by others. The other parts of the demonstration will be beneficial to other (primarily fossil) carbon conversion processes.

In sum, the system builder FZK has demonstrated a capacity to strengthen the *direction of search* and *legitimation* and was, therefore, able to attract Lurgi to the project. With Lurgi becoming the new principal owner of the complete technology chain, it also took over the main responsibility of undertaking system building activities in the alliance.

FZK also strengthened *resource mobilisation* by attracting further financing from FNR. With the additional resources, in combination with collaboration with Lurgi, it was able to construct a new demonstration plant and take the first steps towards demonstrating the entire value chain. With the construction of the new demonstration plant, the actors strengthened the functions of *materialisation* and *entrepreneurial experimentation*. In addition, with the new demonstration plant they secured access to a science and technology infrastructure that will serve as a basis for further strengthening *entrepreneurial experiments*, *knowledge development* and *materialisation*. The success of the demonstration activities is, however, still very uncertain.

The future of the FZK technology option

Beyond the challenge of reducing the short-term technical uncertainties lies the greater challenge of addressing institutional and organisational uncertainties in order to form a market for second-generation fuel from straw. The general institutional uncertainties concerning *market formation* are addressed in Chapter XI. This section will instead discuss the specific challenges of market formation for the FZK bioslurry concept.

The main challenge for the alliance will lie in reducing the organisational uncertainties associated with *market formation* based on a decentralised bioslurry production system, as well as the market and institutional uncertainties around the cost at which the concept can become competitive with other alternatives. The idea behind decentralised production of bioslurry has been that a group of farmers would be able to invest in a plant suitable for a smaller area.[164] The bioslurry would then be transported to a central location for gasification in an EF reactor (GSP or MPG).

The ideal size of the production and its possible integration with other industrial processes have been analysed by various actors (Zwart et al., 2006b; Leible et al., 2007; Zwart, 2007; RENEW, 2008). Lurgi's Dr. Berger (2008) argues that FT diesel production will be too expensive on a small-scale and a more feasible option is the MtG process that is currently being developed. The typical output of such a plant would be 14,000-15,000 b/d (750,000 t/a).[165]

Approximately 40 bioslurry plants would be required to support the operation of such a large, centralised plant. The coordination challenge is thus obvious: simultaneous investments in 40 or more bioslurry plants would need to take place and come into operation at the same time as a refinery.[166]

A potential solution would be to decrease the amount of coordination required by integrating the MtG production facility with a first-generation bio-ethanol and a biodiesel production plant, each with a capacity of 100kt/a. Zwiefelhofer (2007) illustrates that with the waste residues from plants based on first-generation biofuel production, one would only need an additional five larger slurry plants with a output of 26t/h of bioslurry (approximately 40t/h or 320,000t/a of dried straw). The simultaneous investments for this concept would be less difficult to coordinate, even though the capital investment would be very large.

Cost calculations based on the FZK/Lurgi concept have been not considered for the MtG process, but rather focused on FT synthesis. These calculations illustrate a wide range of

[164] For the economics of the production to be manageable, the transportation distance to each plant should not exceed 25-30km. In a farming area in central Europe where this transportation distance is not exceeded, about 45 percent of the typical straw harvest corresponds to a throughput of approximately 200,000 tonnes annually (25t/h and 8,000 hrs per year). This input would generate an output of 134t/a, with 12 times the energy content of the straw and containing 90 percent of the original energy content (Henrich et al., 2007).

[165] 1 boe= 6.8 toe, 14 000*365/6.8 ≈ 750,000

[166] In the meantime, the slurry plants could eventually find alternative applications, but the values of these are highly uncertain.

results depending on a) the cost of the feed-stock, b) the size of the central refinery plant, and c) whether it is integrated into an existing refinery site or a greenfield operation. Leible et al. (2007) illustrate that a production cost of €1.25/litre and €1.0/litre can be reached if the size of a central gasification unit ranges between 500 and 5,000MW_{th} (0.12Mt/a to 1.25Mt/a). Zwart et al. (2006b; 2007) suggest that the cost can be reduced if production takes place in an 8,000MW_{th} FT production facility. A production cost of €0.5/litre could be reached if overseas slurry production was utilised. This would, however, require approximately 80 bioslurry facilities and thus put even greater emphasis on the actors' ability to coordinate simultaneous investments. In a third study, undertaken within the RENEW project, the cost of producing the fuel was estimated to be €1.35-1.79/litre diesel equivalent at 2004 prices. This was applied to a central production site with an output of greater than 1 million tonnes annually and was based on an expected price of biomass in the range of €4-7/GJ (RENEW, 2008).

All of the above estimates are very uncertain but it is possible that the FZK and Lurgi concept will be competitive at an oil price of \$100-150/bbl in a smaller scale facility based on domestic EU resources, and at a price of \$60-100/bbl if larger facilities can be realised in combination with cheaper straw resources from overseas (see Chapter III).

It thus appears that the FZK/Lurgi solution would result in a more costly liquid than the Choren solution, if domestically grown straw is used and the scale of operation is relatively small. With the possibility of integrating production with first-generation biofuel production, the relative competitiveness of the concept may be improved, but further cost calculations are needed to support such an argument. Since the cost of straw makes up one-third of the total cost of production, access to cheap residue can further increase the competiveness of the solution. The basic problems of market formation are thus similar for the two competing alliances promoting large-scale gasification for transportation fuels. Both solutions are considerably more expensive than the production of first-generation fuels, even if their substitution potential has been estimated to be much greater. The main question of market formation and institutional alignment will be dealt with in Chapter XI.

6.1.3 ZSW

Parallel to the development of large-scale solutions for the production of liquid transportation fuels by Choren, FZK and Lurgi, an alternative has been making quiet progress. The research institute Zentrum für Sonnenenergie und Wasserstoff-Forschung (ZSW), located in Stuttgart, has taken on the role of system builder in this project and has created an alliance for the development and promotion of BioSNG based on the FICFB process, originally developed in Güssing (Chapter V).

The evolution of small-scale gasification for the production of synthetic natural gas

ZSW was founded in 1988 with the purpose of conducting research in the field of solar energy and hydrogen technology, and transferring the results of this research into industrial application.[167] The founders and owners of the institute are the state of Baden-Württemberg and a number of public research organisations and private companies with local interests in and around the Stuttgart area. It has therefore been important that the research activities undertaken by ZSW strengthen the industry in and around the Stuttgart area.

Since the institute was founded with the explicit purpose of researching possible industrial applications in solar energy and hydrogen technologies, it provided funding and clear direction to researchers with regards to which areas they should explore (*resource mobilisation, direction of search*). A team of researchers began elaborating on a concept in which higher levels of hydrogen could be obtained when converting carbon-based materials to gas.

The concept, Absorption Enhanced Reforming (AER), is a process in which the CO_2 produced during steam gasification, or steam reforming, can be separated from the reactor by an absorbent. Using the AER process, the resulting gas will contain an elevated level of hydrogen and lower concentrations of carbon oxides than would otherwise have been the case. The process was first tested on natural gas reforming with good results. However, the focus was shifted to biomass since the researchers at ZSW believed that the advantages of the process would be even greater (Specht and Zuberbühler, 2007).

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[167] http://www.zsw-bw.de/ Accessed 2010-04-14.

In 2001, the researchers began to evaluate a range of gasification technologies in order to find the best possible one to adapt for hydrogen production based on biomass. While they found very few suitable solutions, they eventually came across the FICFB Güssing process, and identified it as an attractive option in combination with the AER process (Specht and Zuberbühler, 2007). Collaboration was initiated between ZSW and the actors associated with the Güssing technology, and a consortium of actors interested in developing the AER process was established. The consortium received financial support from the European Commission and the 5th Framework Programme for the research project AER-GAS I & II (*resource mobilisation*).

The Güssing facility was the largest demonstration facility within the consortium and provided unique opportunities for testing and demonstrating the concept on a larger scale. Since the research infrastructure was already in place, the ZSW researchers were able to shorten the development process considerably (*positive externalities*). The results from the Güssing facility became very important for developing the AER process, and could be done at a low cost compared to building a similar demonstration plant themselves (*knowledge development and entrepreneurial experimentation*) (Specht and Zuberbühler, 2007).[168]

Encouraged by their success, the ZSW researchers wanted to continue developing the concept. However, the attractiveness of setting up a standalone hydrogen production site for a future "hydrogen economy" lost its appeal after the turn of the century. However, an alternative application had emerged during the development work that took place at Güssing. The actors at the Güssing facility had experimented with many different technology options and non-electricity uses for the product gas (Chapter V); the option that was identified as having the greatest potential was the production of synthetic natural gas (SNG).

Methane (CH_4) is a less complex molecule compared to synthetic diesel and thus uses less energy to synthesise. Standalone SNG production would therefore appear quite attractive, since as much as 60-70 percent of the energy content can be converted to methane,

[168]During the demonstration of the technology in Güssing, the actors from ZSW were able to demonstrate above 50 percent H_2 content in the product gas, compared to previous 40 percent, but they remain confident that close to 70 percent can be reached. The demonstration also showed that the amount of direct methane was increased and the amount of CO_2 and CO were reduced (Marquard-Möllenstedt et al., 2004).

compared to only 30 percent if electricity is produced at the scale of 10-50MW. In addition, it has been shown that methane synthesis can be performed at atmospheric pressure and clearly benefits from elevated hydrogen content in the product gas (Marquard-Möllenstedt et al., 2004; Zwart et al., 2006a).

A solution which includes the production of BioSNG would better suit the structure of the German heat market since it lacks large heat sinks such as district heating systems. These "discoveries", as a result of the existence of *positive externalities,* clearly changed the *direction of search* for ZSW since 2000, making standalone hydrogen production less interesting to pursue and BioSNG production increasingly so.

Instead of continuing to work with the Güssing plant and Repotec to further demonstrate and commercialise the technology, ZSW formed an alliance of companies from in and around the Stuttgart area with the ability to take the technology to the market. The goal of the project is to build a CHP gasification plant based on the AER process, conduct experiments and develop the BioSNG technology from a slipstream (Specht and Zuberbühler, 2007; Naab, 2008).

The other main actor in the project, aside from ZSW, is the local utility Energieversorgung Filstal (EVF), which has its head office in Göppingen. EVF will be the operator of the future plant. Although the company's main business is natural gas, EVF invested in a CHP plant because it had identified BioSNG based on local resources as an innovative and interesting niche product that it would like to explore further. In combination with gas from fermenting plants, EVF believe BioSNG could give it an advantage over competing gas suppliers in Germany (Naab, 2008).

However, moving directly to BioSNG production was not seen as an option for ZSW. The methane synthesis process must be further developed and the incentive structure for feeding BioSNG into the gas grid has so far been inadequate in motivating the construction of such plants. A step-by-step approach was adopted instead, similar to the Güssing case, in which the plan has been to first construct a 10MW gasification plant for electricity and heat production. Supported by Germany's Renewable Energy Sources Act (Erneubare-Energien-Gesetz, EEG), the plant would carry its own investment and operating costs. It will, however, be considerably more expensive than a conventional combustion technology plant and total investment cost has been estimated as approximately €18 million (Naab, 2008). The main portion of the investment for the CHP gasification plant will be paid by the investment consortium, although investment subsidies will also be necessary (Specht and Zuberbühler, 2007; Naab, 2008).

Based on the continuous operation of the plant, a technology platform will be set up for developing the AER process further, with the intention of producing BioSNG in the future. Technology development with regard to BioSNG and other applications for the hydrogen-rich gas will be conducted based on a slipstream from the CHP gasification plant, and has not been included in the above-mentioned budget. The plan has been to fund the technology platform through the National Hydrogen and Fuel Cell Technology Innovation Programme (NIP), which was set up in 2008. The programme has a budget of €1 billion and has been a part the German government's efforts to maintain its position as one of the world leaders in fuel cell and hydrogen technologies.

In sum, ZSW has a strategy of a "catching-up learner" (Lundvall and Johnson, 1994, p.27). This strategy allows it to benefit from positive external economies and, as a result, get a lot for "free". For example, by not having to develop the necessary infrastructure it can concentrate on improving and developing existing ones. The researchers at ZSW demonstrate their capacity as system builders by strengthening *resource mobilisation* and by setting up a research consortium for exploring the AER process. By using the research infrastructure already in place in Güssing, they can further strengthen *knowledge development* and the *entrepreneurial experimentation* of the TIS. Through the experiments taking place at Güssing, the researchers soon realised that the best application may perhaps be the production of BioSNG, and not hydrogen or electricity, in combination with the AER process. This conclusion *influences the direction of search* and the *legitimation* of the technology, since it clarifies its potential. However, even though ZSW has taken on the role of "catching-up learners", most "product or process technologies borrowed from abroad do not automatically fit into new institutional set-ups." (Dalum et al., 1992, p.311). Consequently, they created an alliance with local firms in and around the Stuttgart area to continue to develop the technology and align it to Germany's own institutional set-up. The following section will outline some of the remaining challenges for realising the technology in the German market.

The future of the ZSW technology option

The development of the Güssing FICFB process for the poly-generation of heat, electricity and BioSNG takes place not only in Austria (Chapter V), but also in Germany by ZSW, as well as in Sweden by Chalmers and Göteborg Energy (see Chapter VII). At the medium-scale of 10-40MW, these efforts have been successful and quite a few projects for CHP production are about to be realised. The feed-in law—which is relevant for CHP in Germany (and in Austria until 2006)—is being used to advance the technology towards BioSNG production. The law permits the construction of plants (*materialisation*) that can be used as platforms on which to perform additional experiments and, therefore, facilitates *knowledge development,* and *entrepreneurial experimentation*, from which valuable lessons can be drawn and complementary technologies developed.

The TIS actors in Sweden, Germany and Austria appear to agree that BioSNG would be a preferred product over electricity. The best value and the largest quantities of future BioSNG would be found in its use as a transportation fuel in vehicles (Specht and Zuberbühler, 2007; Naab, 2008; Gunnarsson, 2009). However, the institutional set-up in Germany does not yet support the construction of BioSNG plants.

To realise such a market in Germany, institutional changes and a new type of alliance would have to be created. In terms of the institutional framework, BioSNG would have to compete with natural gas in addition to conventional liquid fuels. When natural gas is used in Germany as a transportation fuel, the CO_2 tax is reduced by half. As a result, even if BioSNG was exempted from tax completely, natural gas would still be considerably cheaper (Naab, 2008). In addition, even if taxes were adjusted so that BioSNG would be favoured over natural gas, investors could perceive such an investment as associated with a large financial risk, since changes in tax policy can be implemented from one day to the next (Gunnarsson, 2009) .

In addition to the required changes to the incentive structure, which can probably be resolved (see Chapter XI), a new set of actors must to be attracted to the TIS in order to develop the necessary complementary technologies. Most notably, a new generation of gas engines must be developed for heavy-duty vehicles. Methane is not a diesel fuel and cannot, with conventional engines, be combusted at the same rate of efficiency.[169] It is also a gaseous fuel and even though cars with gas engines have been developed and sold, it is not seen as preferred option by the main automotive manufacturers in Germany or by the oil industries (Keppeler, 2007; Drescher, 2008; Picard, 2008a).[170] Additional problems that have been mentioned include the considerably shorter driving range of personal vehicles, the need for two gas tanks, and the existence of too few fuel stations in Germany (Specht and Zuberbühler, 2007; Naab, 2008).

Therefore, it is necessary that the automotive manufacturers, gas utilities and/or oil companies enter the TIS if BioSNG is to be developed as a fuel for the transport sector.[171] It remains to be seen what ZSW, as system builder, manages to do to overcome the intentional and frictional resistance of these incumbent industries.

[169] However, with further engine development the same efficiency for diesel engines could most likely be accomplished (Röj, 2009).
[170] Although Daimler and Volkswagen provide vehicles for the market, they claim that they will not actively promote the development of a gas infrastructure (Keppeler, 2007; Drescher, 2008).
[171] At least in terms of supporting the development of new or improved drive trains with higher fuel efficiency, and the construction of an improved and extended infrastructure.

Box 6.2: The role of the German institute CUTEC in promoting technology options[172]

The research institute Clausthaler Umwelttechnik-Institut (CUTEC) was founded in 1990 by the state of Lower Saxony to promote local industry in the field of environmental products. The research focus of the institute is on large-scale equipment, and the state has directed it to focus on areas that can lead to rapid commercialisation, preferably in less than three years.

In 2002, CUTEC was asked by the state of Saxony if they could "do something" in the field of biomass gasification for producing liquid transportation fuels based on residues from farming. Saxony has always been a farming-intensive state, and the idea of energy farming is deeply rooted as a way of developing additional income streams. As such, it was important for CUTEC to develop a concept that could handle a wide range of different feed-stocks produced by farms as byproducts.

Based on their directives and the experience of the CUTEC staff, the institute constructed a 400kW oxygen-blown atmospheric CFB gasifier, including a system for gas cleaning and a pilot plant for developing Fischer-Tropsch synthesis. The CFB was chosen since it had the most flexible feed, although conventional designs had to be adopted for the use of oxygen. Construction was completed in October 2004, and between January 2005 and May 2007 the pilot underwent 1,400 hours of operation, during which the gasifier was adapted to the wide range of feed-stocks.

The current, simple four-step cleaning system creates a clean gas that can be used for FT synthesis. The cleaning system cannot, however, be used in a commercial application and must be further developed. Further development is being pursued under the ABSART programme, which is funded by the state of Saxony at €1.6 million and situated within the EU project ERA Net Bioenergy together with HPC Starck, TU Vienna, Repotec, and the Güssing facility. The gas cleaning project, which runs until 2010, is of vital importance for the large-scale success of low temperature gasification for the production of FT liquids.

In order to take the next steps towards commercialisation, a group of investors created Strohkraftwerk Gronan Plaungs GmbH, which is a consortium formed with the intention of building a 20MW demonstration plant with simple gas cleaning and using gas engines for the production of electricity.

The construction of the 20MW straw gasifier is seen as a very important step for demonstrating their concept on a larger scale before a commercial plant of several hundred MW is constructed. Thus, the investors in the plant are also using the EEG and investment subsidies available for electricity production to learn more about how other products, such as BioSNG or FT diesel, can be realised in the future. In the meantime, they are advancing their knowledge on gas cleaning and synthesis processes.

The role of CUTEC is not to lead the project but to assist as technical experts. They also see themselves as a possible partner for operationalising the plant once it has been constructed. However, for the concept to be realised on a large-scale, they are dependent on even more generous support schemes or special circumstances that can support the production of a fuel with a production cost of approximately €1.30-1.80/l_{de}.

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172 All of the information in this box is based on an interview with Professor Vodegel (2008) at CUTEC and the Renew (2008) study.

6.2 The system builders' transformative capacity, system weaknesses and the potential role of policy

In this section, the four research questions specified in Chapter II will be revisited. Answers to the questions will be provided for the case of Germany by analysing the previously outlined history. The research questions were formulated as:

1) *Who act as system builders in the different national contexts?*
2) *What characterises the nature and extent of the system builders' transformative capacity?*
    a) *How do the system builders make use of the general structure in which they are embedded to form or strengthen the structure and the various functions of the TIS?*
    b) *To which extent do the system builders manage to strengthen the structure and functions of the TIS?*
3) *What are the limits to the system builders' transformative capacity and how can these be explained?*
4) *Given these limits, which system weaknesses remain to be resolved by system builders and policymakers on different levels (national and EU)?*

This section is divided into two main parts. Research questions one and two will be analysed in the first, and research questions three and four in the second. The discussion will thus begin with discussing who have been acting as system builders, and describe the nature and extent of their transformative capacity. The focus then shifts to analysing and explaining the limits of the system builders' transformative capacity, identifying the main system weaknesses and discussing the potential role of system builders and policymakers in addressing these limits.

6.2.1 The nature and extent of the system builders' transformative capacity

With respect to RQ1, it has been illustrated how the start-up company Choren, as well as the three institutes FZK, ZSW and CUTEC, have taken on the role as system builders. In Germany, the technical institutes appear to be particularly important actors that take on the role of searching for and developing opportunities across new knowledge fields. This involves drawing upon the general structure, both nationally and internationally. The institutes may thereby act as "catching-up learners" (Dalum et al., 1992; Lundvall and Johnson, 1994), developing new opportunities for industries. Of course, this role can also be taken by actors besides the institutes such as the start-up company Choren.

Over time, the actors taking on the system building role has changed in the different projects. In the case of Choren, the identity of the system builder was from the start synonymous with that of the inventor Bodo Wolf. However, as the company increased in size and more actors became involved in the technology, the importance of the individual declined and the system building activities were increasingly taken over by Choren and its allies. In terms of FZK, ZSW and CUTEC, the role of the individual was less prominent and the initial system building activities were undertaken by a specific research group. Just as for Choren, the system building activities have been gradually taken over by the larger alliance or network consisting of incumbent actors from the structure in which the system builders are embedded.

With respect to RQ2, it has been demonstrated that the system builders are embedded in a rich general structure that creates unique opportunities for them to mobilise various resources and thereby form and strengthen the TIS of biomass gasification. The general structure is made up of the four elements of technology, actors, networks and institutions belonging to different sectoral system of innovations. The most important features of the structure have already been described in relation to the various projects, especially concerning the actors and technology.

Thus, these structural elements will only be summarised before an extended analysis is presented of the current institutional framework. The nature and extent of the system builders' transformative capacity will then be discussed with regard to their ability to draw upon resources from the general structure for strengthening the TIS for biomass gasification.

The actor structure in Germany includes a set of capital goods firms capable of providing a wide range of technical solutions in fossil gasification for the petrochemical, oil and electricity industries. The history of these firms was described in the introduction of this chapter and in Chapter III. Some of these firms have benefited from the efforts undertaken in former East Germany to develop various thermal conversion processes for the use of lignite. They are also in the position of taking advantage of the rapidly growing market for coal gasification for the production of various chemicals, SNG, transportation fuels and electricity through the IGCC technology. As a result, incumbents have been able to fill their order books and the competencies associated with gasification are now short in supply. As a response to the rapidly growing market for alternative fuels, some of the incumbent capital goods suppliers of equipment for gasification of fossil fuels have developed a business in supplying equipment for the production of first-generation renewable fuels. However, developing coal gasification as a substitute for oil within the European context would probably not be seen as legitimate in the eyes of the public and has, thus, not been pursued.

The actor structure in Germany also includes a set of firms from the automotive industry and the omnipresent agricultural sector. In particular, the automotive industry has developed a joint position against the blending of large volumes of first-generation fuels with conventional fuel, due to what it considers to be inferior fuel properties. Therefore, it has decided to actively promote second-generation fuels from biomass gasification, but without the intention of becoming fuel suppliers themselves.

The emergence of the TIS for biomass gasification has been both intentionally and unintentionally promoted by the institutional framework in Germany. This framework has provided a broad set of resources that the system builders can utilise in the formation and strengthening of the TIS. In parallel with the extensive actor and technology structure, an institutional structure has been developed, consisting of a multitude of more or less technology-"neutral" and technology-"specific" instruments for stimulating the emergence of renewable energy and new industries. With this mix of policy instruments, Germany has set a target of reducing its total CO_2 emission at 40 percent below the levels of 1990 by 2020 (if the rest of the EU can commit to reducing its emission by 30 percent over the same period) (BMU, 2007). The target will be met with a range of measures, including increasing the share of renewable energy in electricity production to at least 30 percent and increasing the share of renewable transportation fuels so that a net emissions reduction of 7 percent can be achieved by 2020 (equivalent to approximately 12 percent energy content) (BMU, 2009).

Since the early 1990s, the principal policy instrument in Germany for stimulating new electricity production based on renewable resources has been the Renewable Energy Sources Act (EEG), or feed-in law. The law guarantees producer of electricity a specified price for electricity produced from renewable energy sources, depending on when the production becomes operational and the type and size of the production facility (BMU, 2008). The law stimulates a wide array of technical solutions and is adapted to the specific cost structure of each technology. The EEG can thus be seen as technology-specific type of instrument, designed with the purpose of creating an initial market for immature electricity production technologies.

For stimulating renewable fuels the instrument of choice has been a general blending quota that stimulates the production of the cheapest commercially available technology at the time. From the outset, the quota target was 17 percent renewable fuels by 2020, based on energy content (BMU, 2007). However, due to the recent debate over the social desirability of using food for fuel, German targets have been more or less harmonised with EU Directive 2009/28/EC. The target has, therefore, been re-defined in terms of achieving a net emission reduction of 7 percent from the transport sector by 2020, which is equivalent to approximately 12 percent bio-fuel by energy content (BMU, 2009).

The law has increasingly been geared to include more technology-specific measures by excluding the blending of first-generation fuels that do not meet certain sustainability criteria. Moreover, by 2015, the fuels will be rated by their respective net contribution to greenhouse gas reductions. The outcome of such a measure is that bio-fuel with a favourable greenhouse balance may be blended with conventional fuels in smaller volumes. Only those fuels with a CO_2 savings potential of at least 35 percent are to be considered for blending; this limit will be increased to 60 percent by 2017. Bio-methane is included in the new legislation and will, therefore, be able to be counted towards the overall target. In addition, a separate target has been set that stipulate 6 percent of bio-methane in total gas consumption by 2020 and 10 percent by 2030 (BMU, 2009).

In addition to these policy instruments there are measures for stimulating energy research and innovation, including demonstration programmes, grants and research and development programmes. Altogether, the 2008 federal budget made about €3.3 billion available for integrated energy and climate policy (BMU, 2007). These programmes, in combination with the above-mentioned targets and incentive structures, should not be seen as tools solely for abating climate change, but also as a part of an industrial policy being pursued by the government with the objective of " … strengthen[ing] the technology leadership of German companies in global markets" (BMU, 2007, p. 7). Bearing the general structure in mind, the nature and extent of the transformative capacity of Choren and the three institutes will now be analysed.

Choren is currently the only privately owned company acting as a system builder within the German TIS. Although being privately owned, Choren has a history that is strongly tied to the former brown coal institute DBI, and the largest facility for coal gasification in eastern Germany, SVP. Given this background, Bodo Wolf, the founder of Choren, was able to draw on a technology and actor structure that was already developed for coal gasification, and adapt it to biomass gasification. The required resources were mobilised from the institutional structure in the form of the technology-neutral development fund that was available in eastern Germany. With these resources, Choren managed to strengthen the technology structure by constructing a first pilot plant (*materialisation*). In doing so, Choren also strengthened *knowledge development*, *entrepreneurial experimentation*, *materialisation*, *legitimation* and *direction of search*.

On the basis of the stronger technology structure and functions, Choren managed to align the technology to the interest of the domestic automotive industry—Volkswagen and Daimler—as they were interested in promoting alternatives with superior fuel properties than the first-generation fuels already available on the market. With the support of Daimler and Volkswagen, the alliance could be extended to include Shell. Shell brought its FT synthesis technology, and since Shell was willing to grant an off-take price on the fuels from a first demonstration facility (at a sub-optimal scale), the required remaining resources could be mobilised for constructing such a demonstration facility.

The institute FZK managed to *mobilise resources* from the existing structure when the nuclear institute had to be re-oriented. With these resources, it managed to strengthen the technology structure of the TIS by developing a process for producing a bio-slurry based on a technology developed by Lurgi for the production of town gas.

The bio-slurry resembles conventional oil in its physical characteristics and is based on low-value farm residues. The process is, thus, relatively well aligned with the preferences of the incumbent capital goods industry of fossil fuel gasification, as well as with agricultural interests in Germany. By changing the physical properties of the farm residues, FZK strengthened *legitimation* and the *direction of search* for using biomass in industrial chemical process. FZK was, therefore, able to form a technology partnership with Future Energy, and mobilise resources from FNR, BMELV and other organisations with agricultural interests in Germany. With these additional resources, a demonstration facility for bioslurry could be constructed. FZK thus strengthens the actor and the technology structure of the TIS, as well as the functions of *entrepreneurial experimentation, knowledge development* and *materialisation.*

However, it was not easy for FZK to strengthen the structure by creating an alliance with incumbents firms that have experience from fossil gasification and the required downstream processes. FZK encountered frictional resistance to biomass gasification from the incumbents due to the strong market demand for coal gasification, while the market for second-generation fuels still had to be developed (*direction of search*). Nevertheless, FZK succeeded in strengthening the actor structure of the TIS by setting up an alliance with Lurgi and the firms necessary to demonstrate the entire value chain. The fact that Lurgi was interested in cooperating with FZK arguably had to do with its extensive experience with first-generation fuels and the expectation that further technology development would strengthen Lurgi's position in fossil gasification (*direction of search*).

ZSW is a relatively new institute, founded in 1988 with the purpose of exploring solar and hydrogen technology and, thereby, strengthening local industry in and around the Stuttgart area. The institute thus provides a *strong direction of search.* It directs the attention of the researchers onto certain areas of focus and provides a structure from which resources can be mobilised. Since ZSW was a relatively late entrant to the field of biomass gasification, it was able to draw extensively on the *positive externalities* produced by the experience and technology infrastructure that was developed in Austria. It also acted to extend the FCIFB trajectory of the TIS to Germany.

ZSW, therefore, draws on the technology and actor structure developed in Austria but also strengthens the same structure by bringing the AER process to the TIS for biomass gasification. By combining it with the research infrastructure created in Güssing—while setting up a research consortium (AER I&II) with funding from the 5th Framework Programme—ZSW was able to strengthen the functions of *entrepreneurial experimentation* and *knowledge development* of the TIS at a relatively low cost. These activities not only strengthened the TIS in Germany but the TIS as a whole.

Over time, however, ZSW came to realise that hydrogen may not be the best end-product, but that the AER process in combination with the FICFB gasification process developed at Güssing would be excellent for small-scale BioSNG production. With the discovery of the new application, the *direction of search* and the *legitimation* of the process was strengthened. Based on the new direction the project had taken, ZSW then managed to strengthen the structure by establishing an industry consortium with the purpose of commercialising the technology. However, it intend to first build a plant that can carry its own operating costs (supported by the EEG law) for the production of heat and electricity, and then use this facility to commercialise the BioSNG technology. The demonstration facility, however, has not yet been constructed.[173]

CUTEC is the third institute in Germany to have played a significant role in developing biomass gasification. It utilised the availability of CFB gasification already developed for less advanced applications to take further steps towards more advanced applications (see Chapters VII and VIII on Sweden and Finland). An alliance between CUTEC and an industrial consortium was established, in which CUTEC plays a very important role in experimenting with and adapting the technology to the needs and desires of their stakeholders, thereby mobilising significant resources for further developing the TIS (*resource mobilisation*). Just as in the case of ZSW, the plan has been to develop the technology for less advanced

[173] The technology is well aligned with the German heat market, which is dominated by small district heating networks and the currently relatively limited availability of biomass in Germany.

applications, utilising the existing institutional structure for strengthening *market formation*, while developing the technology for more advanced applications such as BioSNG or FT diesel production.

In the conclusions of RQ1 and RQ2, the three institutes appear to have institutionalised the system building role, even though a privately-owned start-up company was also found to take on the role. These actors have made use of the general structure in which they are embedded by:

1) drawing upon fossil gasification and existing fossil-based technologies.
2) aligning the technology to the interests of a) the automobile manufacturers, and b) the incumbent capital goods industries of gasification equipment.
3) drawing upon a wide range of technology-neutral and technology-specific instruments to solve climate, job and nuclear crises, as well as for supporting agricultural interests.

As a result, both structure and functions of the TIS have been strengthened. The embryonic structure of the TIS has been strengthened by building various pilot and demonstration plants (technology), attracting actors (actor), and creating knowledge networks and alliances with incumbents (networks). Seven of the functions have been strengthened: *resource mobilisation, knowledge development, entrepreneurial experimentation, materialisation, legitimation, direction of search,* and *the development of positive externalities.* Hence, all functions of the TIS have been strengthened except for market formation.[174]

6.2.2 Limits of the system builders' transformative capacity, system weaknesses and the potential role of policy

Although it was argued that the system builders had been able to strengthen both structure and functions, there are still limits to their transformative capacity. In this section, the limits of the system builders will be identified, as well the resulting system weaknesses and the potential role of system builders and policymakers for resolving these will be discussed.

[174] One could argue that *market formation* was strengthened in the case of Choren through their special agreement with Shell on the future production of liquids from the demonstration plant. However, the agreement is a one-time event, not replicable in the larger scale as any FT liquids have as of yet not been produced at the plant. If the plans of ZSW and CUTEC are realised, *market formation* will also be strengthened for less advanced applications due to the existing institutional framework.

To begin with, it was previously shown that, to varying degrees, the system builders have managed to strengthen all of the functions of the system except for *market formation*. With regard to *market formation*, there has been some early articulation of demand from potential customers: Choren was able to reach a deal with Shell, which has committed to buy the fuel produced by the demonstration plant. However, no second-generation fuels have yet been produced in any of the demonstration facilities, even though a science and technology infrastructure has materialised in Germany consisting of pilot plants and demonstration facilities.

This infrastructure can potentially be used for demonstrating the production of second-generation fuels, thereby strengthening *market formation*. However, the actors have so far been limited in their capacity to strengthen *knowledge development*, *entrepreneurial experimentation* and *materialisation* to a level where the actors' know-how is sufficient for making the technology operational on the scale of demonstration plants.[175]

The first system weakness is, therefore, an incomplete technology structure and lack of know-how for taking the demonstration plants into operation.

Although difficult to assess, the three major alliances formed by Choren, FZK and ZSW appear to have access to the competencies required to address this system weakness. Nevertheless, it may take years before they can overcome this weakness—the actual time and resources required to fully address it is very difficult, if not impossible, to predict even for experts. Addressing the first system weakness, is thus an unpredictable and potentially costly process.

The system builders will most likely be limited in their ability to pursue *knowledge development*, *entrepreneurial experimentation* and further strengthen *materialisation* over extended period of times without additional support from policy. The role of policy should, therefore, be focused on supporting the process with so called "patient capital" (cf. Donner-Amnell (2000)) in terms of sufficient research and development funding to foster such activities—even if they take a long time to produce results. This "patient capital" will

[175] This can probably be explained by the fact that the actors began experimenting with the technology relatively late and have little or no experience with less advanced applications based on EF gasification of biomass.

probably be particularly important to FZK and Choren, as they will not be in a position to make money on less advanced products while improving the technology for more advanced products. This option is being pursued by ZSW and CUTEC by mobilising resources from the current institutional structure in support for renewable electricity from biomass.[176]

If the demonstration plants can be made operational within the next few years, the technical uncertainties around the construction of subsequent plants can be reduced. Demonstration plants that are successfully up and running would considerably strengthen the *legitimation* and *direction of search* of the TIS, and *positive externalities* may arise. On the other hand, if one or several of the projects fail, there may be negative externalities in the form of reduced legitimacy.

The function of *market formation* would be strengthened if the demonstration plants are successfully constructed and taken into operation (in that a supply of fuel is made available). This would not, however, guarantee that markets are formed. On the contrary, all the system builders in Germany agree that the current institutional framework is not aligned with the technology and that market uncertainties are substantial.

However, even though the system builders share a common understanding that the current institutional framework is insufficient, they have so far been limited in their capacity of strengthening market formation in support of the first commercial-scale demonstration plants and beyond.

So far, the system builders have been able to considerably strengthen the actor structure of the TIS by setting up alliances and knowledge networks across the different projects, not just in Germany but also throughout Europe. Many firms, institutes, universities and other actors interested in various aspects of the process have, therefore, entered the TIS. A crucial factor in this has been the funding made available through various EU Framework Programmes such as RENEW and AER I&II (coordinated by Volkswagen and ZSW). These networks have

[176] Ultimately, whether any of the technology solutions proposed by the above-mentioned actors will work is impossible to predict. To reduce technical uncertainty it may very well be necessary to further strengthen *market formation* and *materialisation* in order to attract other actors to the TIS. These actors could strengthen the technology structure by experimenting with new trajectories or technology options, as well by extending the existing science and technology infrastructure. However, such a structural and functional weakness has not been identified in the German case, since the scope of technical options is still quite encompassing.

focused on developing the technical aspects of the technology, assessing the biomass and market potential, as well as conducting well-to-wheel analysis.

In contrast to the Austrian case, there is thus not a lack of actors with substantial resources in the TIS. Rather, there are cognitive limitations and underlying conflicts between the actors concerning which future solutions are considered "the best". The system builders see each others as fierce competitors and spend much time arguing about "petty politics", and downplay each others' technical solutions rather than finding a common agenda. Therefore, they have not been able to transform the knowledge networks into broader political networks, developing a common agenda for aligning the institutional framework and, thereby, strengthening market formation. Hence,

The second system weakness is the absence of joint political networks necessary for aligning institutions and technology.

The various actors and system builders would all benefit if they pooled their resources, "ran in packs", and argued for an institutional change that would enable market formation beyond the demonstration stage. As Van de Ven (2005, p. 373) argues:

"Technological innovation is fundamentally a collective action process of building an infrastructure that reduces the time, costs, and risks for each participating member"

Since the actor structure of the TIS consists of many powerful actors, agreeing on a common goal would increase their chances of aligning the institutional framework significantly. In a sense, cooperation between the competitors, VW and Daimler, already occurs regarding the development of the common fuel standard and in their common position on the promotion of FT diesel. However, this would also have to be extended to include the other actors within the TIS and concern the general market conditions for second-generation fuels.

In spite of the second system weakness, the activities undertaken by the various system builders have strengthened the *direction of search* and *legitimation* of the TIS. As a result, it is more than likely that the legal framework for biofuels has been partly aligned in Germany and in the EU as whole in support of a market for second-generation fuels. To reach the 10 percent target by 2020, Directive 2009/28/EC states that " … it is essential to develop and fulfill effective sustainability criteria for biofuels and ensure the commercial availability of second-generation biofuels" (EC, 2009a, p. 17). Furthermore, it is argued that the binding character of the directive is "subject to the availability" of these types of fuels. The reasons for policy to address this remaining system weakness from an EU level—as well as the possible forms of intervention—will be further analysed in Chapter XI.

In addition to these two system weaknesses, which are relevant for all the system builders in Germany, there are system weaknesses that are specific to the individual trajectories. One such weakness concerns both Choren and FZK, and refers to the fact that both of their projects rely on the formation of a supply chain that is able to supply large amounts of biomass and bioslurry to a central location. In the case of Choren, it involves securing the future biomass supply for a commercial-sized plant by managing contracts with fuel supplies in the range of 1 million tonnes of locally produced biomass per year. This challenge may, however, be even more difficult for FZK/Lurgi to address. Their distributed solution requires up to 40 slurry plants that need to be up and running before the slurry-oil can be used in a centrally located gasification plant.

Due to the second system weakness—poor political networks that limit the system builders' capacity to strengthen market formation—there are weak incentives for the creation of a supply chain for the production and distribution of bioslurry, torrefied biomass, short rotation coppice and other types of biomass necessary for large-scale production of second-generation transportation fuels based on the EF gasification process. Hence,

The third system weakness is an incomplete actor and technology structure for organising a supply chain capable of handling large-scale production and distribution of biomass suitable for EF gasification.

Overcoming this system weakness will require that the system builder has the ability to coordinate multiple investments in the upstream value chain. It appears as if coordination is a strength for both FZK and Choren, which have been able to coordinate the actions of various down-stream suppliers. If the two first weaknesses can be overcome by the system builders and policymakers, the third system weakness may well be addressed by the system builders without any further policy intervention.

With regard to ZSW, it was argued that it has limited capacity to strengthen *legitimation* and *direction of search* for using BioSNG as a transportation fuel, mainly due to intentional and frictional resistance from the automotive and petrochemical industries, as well as from the major gas utilities (controlling the downstream use of the gas from their process). The automotive sector would need to develop new and improved gas engines, increase the driving range of gas vehicles and develop diesel engines for heavy-duty vehicles that can run on methane with the same or higher rate of energy efficiency. If the market for personal vehicles is targeted, the incumbent gas suppliers would need to build an increased number of filling stations. Hence,

The fourth system weakness is the lack of an actor and technology structure for using BioSNG as a transport fuel.

Direction of search could eventually be strengthened if the system builder creates an alliance or forms a network with first-generation biogas producers, thereby strengthening the actor structure of the TIS. Policymakers could address this system weakness by a) improving the conditions for using BioSNG as an alternative fuel in Germany, i.e. by changing the current tax legislation, and b) supporting the creation of networks with incumbent industries by financing, for example, engine development and the creation of an improved fuel infrastructure.[177]

6.4 Conclusions

By analysing the five most prominent projects for biomass gasification in Germany, four system builders were identified—the start-up company Choren and three research institutes FZK, ZSW and CUTEC.[178] It was concluded that the institutes appear to have institutionalised the system building role by developing an expertise in searching for and developing opportunities across new knowledge fields, contributing to the creation of new TISs. This involves identifying opportunities and drawing upon the general structure, both nationally and internationally. The institutes thereby act as “catching-up learners” (Dalum et al., 1992;

[177] If these weaknesses are not addressed, ZSW will risk being in the same situation as Güssing (Chapter V), in that they will continue strengthening *knowledge development*, *resource mobilisation* and *entrepreneurial experimentation*, thereby creating many new technical opportunities—but without simultaneously creating the industrial capacity to take them to the market.

[178] It was concluded that TU Freiberg had not acted as a system builder (see Box 6.1).

Lundvall and Johnson, 1994) and develop new opportunities for industry. It was also concluded that the actors taking on the system building role changes over time. At the start, individuals such as Bodo Wolff or small research groups at the different research institutes took responsibility for undertaking system building activities, but with time the system building is taken over by the alliances or networks created by the system builders.

By making use of the rich structure in which they are embedded, the system builders have been able to create the embryonic structure of the TIS. By building various pilot and demonstration plants (technology), attracting actors (actor), and creating knowledge networks and alliances with incumbents (networks), the system builders have strengthened the structure and all functions except for *market formation*.

However, although the system builders have strengthened the structure and the functions of the TIS, they have not yet managed to take the first demonstration plants into operation. They have also, so far, failed to develop the political networks required to align the institutional framework and the technology so that a market formation for commercial-scale plants is enabled. Hence:

1) *The first system weakness is, therefore, an incomplete technology structure and lack of know-how for taking the demonstration plants into operation.*

2) *The second system weakness is the absence of joint political networks necessary for aligning institutions and technology.*

The first system weakness has to be addressed by the provision of sufficient funding through policy, so that the demonstration plants can eventually become operational. This may take a long time and the role of policy would be to provide "patient capital" (Donner-Amnell, 2000) for the first plants to succeed. If the first one or two demonstration plants fail before others succeed, it would most likely create negative externalities and significantly decrease the legitimacy of not only the specific trajectory but of the TIS as whole, reducing the possibility of other projects to materialise in Europe.

The second weakness has not been resolved by the system builders since they see each other only as competitors. Hence, even if they agree that the current framework is insufficient, they have failed to create the necessary political network and formulate a commonly supported alternative. Since the actor structure of the TIS consists of many powerful actors, agreeing to and working on a common goal would increase their chances of aligning the institutional framework.

In addition to the two system weaknesses that are relevant to the four projects, two additional weaknesses exist: one concerning Choren and FZK and the other concerning ZSW.

3) *The third system weakness is an incomplete actor and technology structure for organising a supply chain capable of handling large-scale production and distribution of biomass suitable for EF gasification.*

4) *The fourth system weakness is the lack of an actor and technology structure for using BioSNG as a transport fuel.*

It was argued that if policy can address the first two system weaknesses, the system builders are likely to coordinate the creation of the necessary supply chain for bioslurry and biomass in the required quantities. With regard to the fourth system weakness, it was argued that the system builder need to create alliances or form networks with first-generation biogas producers to strengthen the actor structure of the TIS. Policymakers will be required to finance and support the formation of such networks and alliances to also include the automotive industry for engine development and eventual test fleets, as well as for extending the fuel infrastructure.

Sweden

Chapter VII
Sweden

The history of biomass gasification in Sweden is relatively long compared to that of Austria (Chapter V) and Germany (Chapter VI). Since the 1970s, it has evolved along two main trajectories over three main episodes. Each episode has been dominated by a *direction of search* and an actor structure interaction specific to the TIS of biomass gasification in Sweden.

The first episode began during the 1973 oil crisis with the first serious experiments on biomass gasification since the Second World War. The *direction of search* was influenced by a desire to create a substitute for oil, and methanol was identified as the preferred alternative fuel at the time. The favoured feed-stock was peat and biomass, but experiments were also conducted using coal and extra-heavy oils. These early experiments gave rise to two main trajectories. The first to emerge was focused on stand-alone fluidised bed gasification. The second was based on the integration of entrained flow gasification of black liquor in chemical pulp mills.[179]

In 1986, the *direction of search* rapidly shifted towards large-scale production of electricity due to a sudden drop in the price of oil and the Chernobyl nuclear accident. As a result, other actors became interested in the technology and further attempts were made to develop it (although no real commercial break through was made by Swedish actors). Interest in new electricity generation based on biomass gasification decreased during the late-1990s, mainly due to the deregulation of the electricity market and less political pressure placed on the decommissioning of nuclear power.

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[179] The first attempts with black liquor gasification were, however, intended to produce electricity and not transportation fuels.

Nevertheless, the gasification of renewable resources became fashionable once again when the threat of climate change was initially recognised and the technology was identified as strategically important for realising the production of renewable transportation fuels in large quantities.

This chapter is divided into four main sections. The first section will describe the history of fluidised bed gasification from 1973 to 2009. The second will outline the evolution of the entrained flow gasification of black liquor in approximately the same time period. The first two sections will focus on describing the interactions between actors and the characteristics of the emerging technological innovation system (TIS). The focus is on how the system builders act to create the emerging structure of the TIS by building the structure directly, but also by strengthening the various functions specified in Chapter II.

The third section of this chapter provides answers to the research questions (as specified in Chapter II). The discussion will start with identifying who have been acting as the system builders, and then describe the nature and extent of their transformative capacities. The focus then shifts to analysing and explaining the limits of the system builders' transformative capacity, identifying main system weaknesses, and discussing the potential role of system builders and policymakers in addressing these weaknesses. The fourth section of this chapter presents the main conclusions.

7.1 Three episodes of fluidised bed gasification in Sweden, 1973–2009

This section will describe the development of fluidised bed gasification in Sweden from when it started during the first oil crisis in the early-1970s up to 2009. The section is divided into the previously mentioned three episodes. Following the final episode, a project developed by Göteborg Energy will be described in a box. This project is not really an outcome of the history of gasification in Sweden, but is more related to the recent development of FICFB gasification in Austria (see Chapter V). The section concludes with a summary of the three episodes.

7.1.1 Episode I: 1973–1986. The oil crises, transportation fuels and lime kilns

At the beginning of the 1970s, the district heating and transportation sectors were almost completely dependent on cheap oil. As such, when the first oil crisis hit in 1973, a wide range of initiatives were undertaken to reduce this level of oil dependency (*direction of search*).[180]

The focus of government spending on biomass gasification was on developing methanol production based on domestic resources. The intent was to use the methanol in the transportation sector in order to reduce oil dependency (Sandén and Jonasson, 2005). While there was a need to increase electricity production at the time, the parties in parliament, the military and leading scientists essentially agreed that nuclear power was the preferred choice over any other alternatives (Kaijser, 1992; Anshelm, 2000). As a result, developing biomass gasification for electricity production did not interest the government at the time.

As a consequence of the oil crisis, the funding for Professor Olle Lindström and his research group at the Royal Institute of Technology (KTH) significantly increased. He received dedicated funding from the government to start experimenting with various new energy technologies, that could potentially reduce oil dependency (*resource mobilisation*) (Rensfelt, 2008).

One of his students, Erik Rensfelt also received funding from the regional research council Norrlandsfonden, with the objective of developing the industry in northern Sweden. His task was broadly defined as "to do something interesting with peat".[181] Consequently, Mr. Rensfelt started experimenting with peat gasification, constituting the first serious peat and biomass gasification experiments in Sweden since the first time since the Second World War (Rensfelt, 2008).[182]

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[180] Between 1970 and 1974, the price of oil increased by approximately five times, from $10 to $50 per barrel, in 2008 dollars (BP, 2009).

[181] The peat resources in northern Sweden are vast and had previously been developed as an emergency fuel in the case of war (Hellsmark, 2005)

[182] These first activities at KTH continued and eventually evolved into a research group at KTH, which still focuses on various aspects of biomass gasification (Rensfelt, 2008; Sjöström, 2009).

The need to reduce oil dependency became even more pressing in the wake of the second oil crisis in 1978-1979 (*direction of search*).[183] As a result, government efforts in support of the development of alternative technologies intensified, and researchers involved in biomass and peat gasification were offered more money than they could find time and people to spend it on (*resource mobilisation*) (Rensfelt, 2008). The government also directed (*direction of search*) both the Technical University in Lund (LTH) and KTH to develop biomass gasification with the goal of building a pilot plant in Studsvik for methanol production based on domestic fuels (Rensfelt, 2008). Consequently, the process development of gasification technology moved from KTH to Studsvik, while research on the science behind the process still continued at KTH.[184]

Studsvik had been developed as a government-owned research and development laboratory for energy technologies. It employed more than 600 scientists, but the vast majority was engaged in developing nuclear technology for electricity production. However, most of the government resources allocated to Studsvik were for developing alternative energy technologies such as solar and wind power. The process development of biomass gasification continued at the Department for Thermal Processes at Studsvik, which initially employed about 20-25 individuals (Waldheim, 2005, 2010).[185]

By 1980, the Studsvik researchers had constructed a pressurised oxygen-blown $2MW_{th}$ bubbling fluidised bed (BFB) pilot plant that could be operated at a maximum 25 bars of pressure. The pilot plant (MINO) was intended for methanol synthesis. The pilot plant operated successfully from 1980 to 1986, and was tested with a wide range of biomass-based fuels. It was considered the most advanced pressurised biomass gasification process at the time (Blackadder et al., 1992; Rensfelt, 2008). With the completion of the pilot plant, the actors strengthened the functions of *knowledge development*, *entrepreneurial experimentation* and *materialisation* of the emerging TIS.

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[183] Between 1978 and 1979, the price of oil more than doubled from $46 to $96 per barrel (BP, 2009).

[184] Researchers at KTH interpreted this as an explicit request from the government to engage in scientific research on the gasification process but not on process development itself. This practice was later institutionalised at KTH, in that they do not develop new processes. However, their research still requires access to experimental research equipment (Sjöström, 2009).

[185] The research and experimental activities at the Department for Thermal Processes took place in close cooperation with Svensk Metanolutveckling AB (SMAB), who performed different motor tests and evaluated methanol as an alternative transportation fuel (Sandén and Jonasson, 2005).

With the completion of the pilot plant, the researchers at Studsvik considered the process ready for scaling up. To do so, they sought to increase collaboration with European contractors, and in 1986 Linde made an offer to the Finnish chemicals company Kemira based on the MINO process technology (Waldheim, 2010). These initiatives were undertaken because Kemira was interested in constructing a commercial-scale, $80MW_{th}$, peat-based gasification system for ammonia synthesis in Oulu, Finland (*market formation*).[186] The project would receive substantial investment support and funding from the Finnish government for the research and development work involved. It was thus an attractive project for both Studsvik and Linde. However, competition from two other suppliers resulted in them losing the contract; the German engineering firm, Uhde, with extensive experience in oil and coal gasification for various synthesis processes—won it instead (see Chapter VIII).

In parallel with the development of pressurised gasification systems, an alternative and less advanced application for biomass gasification was being explored by Götaverken and its main competitor in Finland, Ahlstrom (see Chapter VIII). Together with the pulp and paper industry, Götaverken had developed an atmospheric circular fluidised bed (CFB) gasification processes for oil substitution in lime kilns. The application did not require any advanced gas cleaning and enabled the pulp and paper industry to utilise residue feed-stocks from the mills such as bark and other types of waste wood.

Since the commercial success of pressurised gasification for methanol synthesis had been difficult to achieve, Studvik also took an interest in the market for less advanced applications and developed their own CFB atmospheric lime kiln gasifier in cooperation with Fläkt Industri AB (later ABB Fläkt Industri AB).

Studsvik was also selected for a project in Italy, Grevé-in-Chianti, in which they installed two $15MW_{th}$ atmospheric refuse-derived fuel (RDF) gasifiers, based on their lime kiln gasifier and without hot gas cleaning, in which the gas was fed into a conventional boiler (Blackadder et al., 1992; Waldheim, 2010). The project was important as Studsvik gained commercial experience, a reference plant and experience with working with large-scale equipment (*knowledge development, entrepreneurial experimentation, materialisation, market*

[186] A synthesis process similar to that for methanol.

formation). The installation was operated with limited success between 1993 and 1997 (Knoef, 2005).[187]

Besides Grevé-in-Chianti, they only made a few additional offers to potential clients before the market collapsed with the rapid decrease in the price of oil in 1986 (Rensfelt, 2008). Thus, the re-emergence of cheap oil marked an end to the first episode of biomass gasification in Sweden.

In summary, the government provided ample resources in support of the development of new technologies for oil substitution during this first episode. These resources made it possible to begin experimenting with biomass gasification for the first time since the Second World War. Guidance on the main development efforts was provided by the government's interest in developing methanol from domestic resources as an alternative fuel (*direction of search*).

In response, various actors entered the TIS, while Studsvik was the main actor in pursuing methanol production based on domestic peat and biomass resources. Even if methanol production failed, all of these actors considerably strengthened the TIS and created positive interconnections involving *resource mobilisation, knowledge development, entrepreneurial experimentation, materialisation, and market formation* for less advanced applications. However, what was not accomplished (nor attempted) was aligning the institutional framework to support the formation of a market (*market formation)* that did not rely on a high price of oil. Thus, when the price of oil dropped, this momentum ceased. Nonetheless, this first episode resulted in the creation of a new structure upon which the next episode could build.

7.1.2 Episode II: 1986–1999. Towards large-scale electricity production

During the first episode, the relevant actors experienced a situation wherein they had access to more money than they could find time to spend. By 1987, however, the availability of cheap oil turned this situation into a crisis and forced the restructuring of energy research in

[187] According to Waldheim (2010), it was operated until 2004.

Sweden.[188] As a result, developing biomass gasification for methanol synthesis suddenly became unattractive. Due to a series of exogenous events, however, a new episode soon emerged, re-igniting interest in the development of large-scale heat and electricity production based on pressurised gasification systems integrated with a combined steam and gas turbine (BIGCC).

The first such event to shift the *direction of search* in favour of biomass gasification had actually occurred during the first episode in March 28, 1979, with the nuclear accident at Three Mile Island in Pennsylvania, USA. Nuclear energy was already controversial in the beginning of the 1970s, and the accident swiftly convinced a majority of Parliament of the need for a referendum on the future of nuclear power in Sweden, which took place in spring 1980 (Anshelm, 2000). Based on the outcome of the referendum, Parliament decided that all nuclear power plants in Sweden should be decommissioned no later than 2010. However, this decision also identified the importance of developing alternatives to nuclear power, so that decommissioning would not jeopardise the welfare of the country (Anshelm, 2000). The referendum did not, however, result in any specific directions as to how a decommissioning should be accomplished, nor in any new incentives for the development of alternative technologies (Anshelm, 2000).

These incentives were not introduced until the second major exogenous event, the 1986 Chernobyl nuclear accident. The Swedish Minster of Energy at the time, Birgitta Dahl, intensified her efforts to organise a swift decommissioning of nuclear power and reinforced her and the government's strong belief in realising the potential of alternative and domestic energy resources. This new rhetoric led to strong reaction from industry and the energy utilities (Anshelm, 2000), who were more or less forced to start looking for alternatives to nuclear power (Ståhl, 2008).

A new *direction of search* was thus created to develop alternative technologies for electricity production based on domestic resources. As a result, the two dominant energy utilities, Sydkraft and Vattenfall, were encouraged (or forced) to enter the TIS for biomass

[188] In 1987, Studsvik Energiteknik AB was renamed Studsvik AB, and its research was divided into the divisions of Nuclear Technologies and Energy Technologies.

gasification. Nevertheless, this new direction of search also created new opportunities for the surviving actors and networks from the previous episode. The activities undertaken by Sydkraft and Vattenfall will now be described.

Sydkraft

Sydkraft evaluated several alternative technologies for producing electricity with the potential of replacing nuclear power. Early on, it considered NGCC and IGCC as the most promising options. Although it was aware of the environmental problems associated with energy production from coal, it saw coal-based IGCC technology as a "clean" coal technology that could be pursued on a large-scale (Ståhl, 2008).

An internal project at Sydkraft was initiated and a vision was developed for a flexible plant in which one could easily shift between different feed-stocks such as biomass, coal and natural gas. Consequently, Sydkraft went ahead with a preliminary study on a $15MW_{el}$ coal gasifier and decided to procure the necessary components for the pilot. Ultimately, this project was terminated in 1989, since the required environmental permits could not be obtained (Ståhl, 2008).

The project did, however, enable Sydkraft to increase its knowledge of gasification. It also allowed the company to identify the potential of offering large-scale electricity production at a high level of electrical efficiency compared to the combustion of solid fuels (*knowledge development* and *direction of search*). This was of particular importance to new energy technologies at the time, if they were to be considered as a realistic alternative to nuclear power.

Public opinion indicated that biomass was, in contrast to coal, considered to be a highly legitimate fuel, although the technical and economical potential of utilising biomass for electricity production was quite controversial. The best estimates of its potential varied somewhere between 7 and 30TWh (SOU, 1991:93). Even if there were disagreements on the size of its actual potential, it was large enough to encourage the introduction of further incentives for phasing out nuclear power in Sweden.

The means of developing biomass-based alternatives to nuclear power were partially created with the "green tax reform" of 1990−1991, when a CO_2 tax was introduced. With the CO_2 tax, the institutional framework was aligned with the use of biomass for district heating (Hellsmark, 2005). The tax reform also created a surplus of SEK 650 million, which were subsequently dedicated to a major demonstration programme for supporting the development of electricity production from biomass, called FABEL (*resource mobilisation, direction of search*) (Tegnér, 2009).[189]

Gasification was thus identified as a process with the potential to produce a lot of electricity based on domestic resources, and once again the government identified it as a strategically important field of knowledge (SOU, 1991:93; Tegnér, 2009). As a result, biomass gasification became one of few (and attractive) options for Sydkraft to explore, since it could no longer expand electricity production with nuclear power, the availability of natural gas was limited and using coal was highly controversial in the eyes of the public.

However, Sydkraft soon discovered that there were no suppliers of commercial BIGCC plants on the market, thus forcing it to conduct its own investigations into how the development of this novel technology would best be pursued (*knowledge development*).

Based on this study, Sydkraft concluded that pressurised fluidised bed gasification integrated with a combined steam and gas turbine was the best way to maximise electricity production from biomass. While its study led to several ideas for solving the technical problems associated with BIGCC, Sydkraft did not want to develop the technology itself and take on the role of a future capital goods supplier. Instead, Sydkraft began looking for a partner who would be interested in developing the technology in collaboration (Ståhl, 2008).

Studsvik was one of the few surviving actors from the first episode and had, together with Götaverken[190] and Fläkt Industri, extensive experience with both pressurised (MINO) and atmospheric FB gasification. With further knowledge development, this experience was seen as important for developing both large- and small-scale BIGCC.

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[189] FABEL - Främjande av biobränsle-el

[190] At the time the name of the company they collaborated with was Generator but it later merged with Götaverken (Waldheim, 2010). For reasons of consistency, only the name Götaverken will be refereed to throughout the text.

In 1988−1989, the Department of Thermal Processes at Studsvik took the first steps towards developing the BIGCC application with a smaller research programme devoted to gas cleaning and based on their atmospheric lime kiln gasifier (*knowledge development*). The research programme did not lead to the materialisation of any new plants, but provided further insights into a knowledge field of strategic importance to the government (Rensfelt, 2008). Studsvik also tried to attract interest from potential customers for using the MINO technology and pilot plant for this application (Waldheim, 2010).

Sydkraft began looking for a partner in 1990 and in so doing, contacted and evaluated all actors with experience in biomass gasification that would be willing to develop the technology in collaboration with it (Ståhl, 2008). However, possible partners for collaboration were few in number.

Amongst these were, of course, Studsvik and Götaverken. Discussions on developing such a plant were held between Sydkraft and the two companies (Rensfelt, 2008; Ståhl, 2008). Sydkraft also discussed this with Götaverken's main competitor, Ahlstrom, which had sold more atmospheric CFB lime kiln gasifiers than Götaverken and was, along with Götaverken, among the world leaders in CFB boiler technology. However, Ahlstrom had limited experience with pressurised systems, although it had long worked with the Finnish research institute VTT, which had gained experience with pressurised systems in collaboration with Uhde at the Kemira plant in Finland (see Chapter VIII). Ahlstrom was interested in collaborating with Sydkraft because the BIGCC technology had also been identified in Finland as an important potential alternative to nuclear power. In addition, Ahlstrom had identified a potential market in countries with less demand for heat and higher electricity prices than in the Nordic countries (Palonen 2008).

The project leader for biomass gasification at Sydkraft, Krister Ståhl (2008), emphasised that it was important for Sydkraft to have a reliable industrial partner to collaborate with. Ahlstrom was perceived as such a partner, while Götaverken and the Department of Thermal Processes at Studsvik AB were not selected.[191] Why Sydkraft did not select Studsvik and

[191] Since the technology was novel and both parties would take part in technology development, Ahlstrom and Sydkraft decided to form a jointly-owned company called Bioflow. The new company became part of the

Götaverken in favour of a Finnish supplier is a difficult question to answer (and perhaps not even meaningful).[192] Indeed, although both Götaverken/Studsvik and Ahlström appeared to have had similar types of experience in the field, there is no reason to doubt that Sydkraft made the best possible choice for succeeding with the project.

In 1991, Sydkraft applied for SEK 50 million from the Swedish government to support the construction of a 18MW_{th} BIGCC in the town of Värnamo (*resource mobilisation*) (Tegnér, 2009). The goal of the project was to design, construct and operate a BIGCC demonstration for combined heat and power generation (Sydkraft, 1997). Sydkraft's priority was clear from the start: it wanted to demonstrate the technology in a fully integrated facility at the lowest possible cost, and it did not aim to demonstrate the highest possible electrical efficiency of the technology (Sydkraft, 1997; Ståhl, 2008).[193]

The size and cost of the demonstration was directly and indirectly determined by the turbines in the plant for two main reasons. First, the turbines were one of the most expensive parts of construction. To keep investment costs down it was, therefore essential to find the smallest and cheapest turbines available, even if this resulted in lower electrical efficiency than would otherwise have been possible (Sydkraft, 1997, p. 19-21).[194] Second, the size of the plant was determined by the gas flow required for operating the gas turbine at full effect (Sydkraft, 2000, p. 18).

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organisational structure of Ahlstrom, which also owned 51 percent of the company (Sydkraft owned the remaining 49 percent). All IPR and development work concerning pressurised BIGCC was transferred into Bioflow, and the plan was to market the technology through that company (Ståhl, 2008; Jönsson and Tillberg, 2009).

[192] In 1990, Götaverken was sold by Svenska Varv to the company Kamyr, which was owned by the Norwegian group Kvaerner. The state also transferred all of its shares in Studsvik AB to the state-owned utility Vattenfall, which was the main competitor to Sydkraft AB.

[193] Instead, the expected output from the project was operational data, information on fuel flexibility, assessments of the cost of operation, and maintenance. Ultimately, the necessary knowledge on how integration could be best designed for future plants at the lowest possible cost and highest possible efficiency would, thereby, be obtained. In the Värnamo demonstration, total plant efficiency was at 82 percent, and electrical efficiency was at 32 percent, based on a wood fuel with 15 percent moisture content. Losses in the fuel preparation are thus not accounted for and real electrical efficiency was even lower.

[194] A Typhoon gas turbine, manufactured by European Gas Turbines (now part of Alstom Power), was chosen, with an effect of 4.2MWel. It was a modern and highly efficient gas turbine. It was, however, combined with a less expensive steam turbine with a moderate efficiency. A more expensive and efficient steam turbine could not be motivated, since the primary purpose was to illustrate the integrated process and not the highest possible electrical efficiency (Ståhl, 2010). Their combined achieved effect was 6MWel.

As a result, the plant in Värnamo was constructed as an 18MW_{th} plant, which was the smallest possible plant for demonstrating the technology in a fully integrated mode. However, it was still a rather large plant and the investment cost amounted to SEK 230 million. Moreover, a "fuel factory" had to be built for an additional SEK 70 million (Ståhl, 2008). During the construction phase, Sydkraft received SEK 53 million, or 18 percent of the total investment cost, from the government (*resource mobilisation*) (Ståhl, 2008).[195]

Sydkraft and Ahlstrom commenced plant construction in September 1991, and after some minor delays the demonstration plant was completed in 1993 (*materialisation*). The plan was to have it in full operation the same year, but due to problems during the start-up of the plant, this was delayed until 1996 (*market formation*) (Sydkraft, 1997, 2000). Such problems should, however, be expected when new technology is developed and all the problems that occurred were eventually solved.

Nevertheless, by the end of 1996, the number of operating hours with the gasifier had reached approximately 3000 but only 400 hours with the gas turbine (Sydkraft, 1997; Ståhl, 2008). Therefore, the demonstration programme was extended until 1999 in order to achieve more operational experience and to test the process with a wider range of biomass and waste feed-stocks (*entrepreneurial experimentation* and *knowledge development*).[196] At the end of the second demonstration period, the Värnamo project was declared a success. The gasifier had been operating for 8,500 hours and the gas turbine for 3,600 hours (Sydkraft, 2000).

With the completion of the demonstration programme in 1999-2000, the power plant was mothballed and put up for sale, since it had not been constructed or planned for continuous operation (Ståhl, 2008). The cost of running the plant continuously was, and still is, higher than the revenue it could generate by selling the heat and electricity it produced (Bengtsson, 2008; Rensfelt, 2008; Ståhl, 2008). The total cost for construction and operation during the demonstration programmes has been estimated to be about SEK 500 million, of which

[195] Of this, SEK 53 million came from Nutek, including "kraftvärmestöd" at SEK 4,000/kW (6MW plant equals SEK 24 million). An additional SEK 45 million came from Svensk Energiutveckling (SEU) AB (which later became part of Elforsk AB). These are, however, not counted as government support since SEU was owned by the industry (Ståhl, 2010).

[196] According to the original time plan, demonstration was planned for 1994-1998 (Ståhl, 2008).

approximately SEK 65 million came from the Swedish government and SEK 45 million from SEU (Ståhl, 2008, 2010).[197]

However, at the end of the demonstration programme, no nuclear plants had been decommissioned. Sydkraft and Foster Wheeler were interested in scaling up the Värnamo concept for commercial operations, but no customers—including Sydkraft— were willing to make the investment and take on the technical and market risks associated with the first full-scale and commercially operating BIGCC plants on a deregulated market (the reasons behind this will be discussed later).

Vattenfall

Vattenfall probably felt, just as Sydkraft, more or less forced by the government to start exploring alternatives to nuclear power. In 1989, they declared that they would invest approximately SEK 1 billion in the Bioenergy Programme. The explicit goal of the programme was declared by the board of directors in December 1989 as [my translation]:

"Vattenfalls goal within the field of bioenergy is to clarify the economics and potential for combined heat and power generation in Sweden over the long-term. Technology development will be an important means for meeting this goal" (Vattenfall, 1991).[198]

The hallmark project of the Bioenergy Programme was VEGA, which was initiated in December 1990. The purpose of the project was similar to that of Sydkraft's Värnamo project, but collaboration between the two utilities was seen as out of the question (Tegnér, 2009).

Hence, Vattenfall also set out to explore the potential of pressurised fluidised bed gasification for combined heat and power generation, integrated with a combined heat and steam cycle (BIGCC). Thereby, Vattenfall entered the TIS of biomass gasification, and based on their programme declaration it was clear that they intended to bring significant resources

[197] For completing the second demonstration phase, Sydkraft received SEK 12 million from FABEL (Tegnér, 2009). They also received some financial support from the EU THERMIE programme, which had financed a Danish IGCC project called BIOCYCLE that was never executed (Ståhl, 2008). Tegnér (2009) has argued that SEK 150 million came from the government.

[198] Original text: "Vattenfalls mål inom bioenergiområdet är att klargöra ekonomi och potential för el-och kombinerad el-värme-produktion i Sverige i ett långsiktigt perspektiv. Teknikutveckling blir ett viktigt medel för att nå detta mål" (Vattenfall, 1991).

to the TIS and to strengthen, at least, *knowledge development, entrepreneurial experimentation materialisation,* and perhaps also contribute to *market formation*.

The VEGA project was initiated the same year as the government transferred the ownership of Studsvik AB to Vattenfall. With the transfer, Vattenfall also became owners of the Department of Thermal Processes, giving it direct access to one of the most advanced pilot plants for the pressurised fluidised bed gasification of biomass in the world and a group of experts with extensive experience in the field.

The Department of Thermal Processes was awarded a contract together with Götaverken to conduct a preliminary study for the VEGA project. A similar study was also awarded to the Finnish actor Tampella Power Oy (Waldheim 1998). In parallel with these studies, Vattenfall undertook its own investigation in which it evaluated different gasification concepts, their possibilities, the required investment levels, the further need for technology development, and possible technology suppliers. In addition, a timeline for demonstrating the technology was established (*knowledge development*) (Vattenfall, 1991).

For the contract, Vattenfall selected Tampella Power Oy and, at the same time, decided that all the activities at Studsvik that were not related to nuclear power would be terminated (Waldheim, 1998; Rensfelt, 2008). The former managing director of the Department of Thermal Process at Studsvik, Mr. Renselt (2008), argued that it was probably cheaper for Vattenfall to collaborate with Tampella, as it had already constructed a larger pilot facility in the town of Tampere, Finland. It did, however, not include an integrated gas and steam turbine (Ståhl, 2010).[199]

Vattenfall's agreement with Tampella created a new company called Enviropower. All the rights to the technology, including the pilot plant in Tampere, were transferred to the new company, which was 75 percent owned by Tampella and 25 percent by Vattenfall (Salo, 2008). Enviropower was then awarded the contract for a feasibility study on a commercial-scale, $60MW_{el}$ BIGCC demonstration facility to be located in the town of Eskilstuna, Sweden.

[199] In 1989, Tampella Power had bought the license for the U-GAS process, developed at IGT (Institute of Gas Technology) in Chicago. The technology was based on a bubbling fluidised bed, developed for coal gasification but for which peat had been tested during the 1980s (Vattenfall, 1994).

In addition, a series of tests and verifications was financed by Vattenfall to be performed in Finland at the pilot plant in Tampere, but also in a small laboratory gasifier that had been constructed at the VTT institute in Helsinki (Vattenfall, 1994). These activities strengthened the know-how of the Finnish actors, as well as the functions *knowledge development* and *entrepreneurial experimentation* of the TIS in Finland.

The investment decision to construct the commercial-scale demonstration facility in Eskilstuna was, however, never taken. Just two years after the collaboration with Tampella was initiated, the preliminary study was terminated.[200] Vattenfall decided to end their plans for a commercial demonstration in Eskilstuna and their relationship with Enviropower. As a result, Enviropower went bankrupt but some of the gasification competencies were later spun-off and the privately-owned firm Carbona Oy was established (Salo, 2008). The remaining parts of Tampella (the majority owner of Enviropower) were then acquired by Kvaerner and subsequently by Metso Power.

Vattenfall's executive committee identified the large volume of investment and the power balance in the Nordic countries as its primary reasons for not developing the technology further (Vattenfall, 1994). The manager of the Bioenergy Programme, Birgit Bodlund (1998), argued that the risk would have been too great for Vattenfall. A commercial plant in 1995 would have cost about SEK 1,000 million and there were, at the time, no sufficiently large funding schemes that could reduce the risk for Vattenfall. Even if it would have received all of the money available under FABEL (SEK 625 million), Mrs. Bodlund argued that it would not have been enough. In addition, she argued that Vattenfall's articles of association did not support the fact that it would engage in new technology development. As a state-owned utility, it was supposed to act as a buyer on the market, but no commercially BIGCC technology was available (Bodlund 1998; Tegnér 2009). This last claim is, of course, contradictory to what was declared in the original intention of the Bioenergy Programme.

[200] The preliminary study was terminated during the summer of 1992, but Vattenfall chose to continue with the testing and verification programme of the technology that had started in Finland. It was completed in November 1994 (Vattenfall, 1994).

TPS

Despite not being selected by Sydkraft or Vattenfall, and being officially terminated by Vattenfall, the staff at the Department of Thermal Process in Studsvik did not give up. Instead of accepting their termination, they decided to start a company that was independent from Vattenfall. They also managed to convince both Vattenfall and the local union that they had the necessary means and know-how to run a successful business. The parties eventually agreed. As a result, they received the money allocated for terminating the department and they were allowed to keep existing government research contracts with the Swedish National Board for Technology Development (STU)[201] (Rensfelt, 2008). As a result, the company Termiska Processer AB (TPS) was created in July 1992. Fifty percent was owned by its staff and management, and the remaining 50 percent belonged to a consortium of mostly municipal energy companies in Sweden (Rensfelt, 2008).

Municipal interest in the company was important. They were interested in accessing the research and development competencies within the company and some of them had substantial interest in pursuing BIGCC, but on a smaller scale than Vattenfall and Sydkraft. An atmospheric BIGCC technology was developed at the size that would be suitable for the district heating systems owned by the municipalities (Johansson, 2005; Peters, 2005).

One of these utilities, Borås Energy, not only conducted a feasibility study but also prepared for installation by acquiring a large drying unit. The management spent a great deal of time securing funding, but failed to convince policymakers to provide funds greater than a 50 percent subsidy. It was argued that such a subsidy was necessary for reducing the technical and financial risks involved to an acceptable level (Peters, 2005). Consequently, Borås Energy (and others) decided to await the results of other potential customers' experience with TPS and its projects outside Sweden.

TPS had been selected by Shell as a partner for a project in Brazil, which was financed through the World Bank (Waldheim, 1998; Rensfelt, 2008). Shell had evaluated all gasification technologies available at the time, including the Värnamo process that was in commissioning at the time. Waldheim (1998) and Rensfelt (2008) argue that TPS won the

[201] STU - Styrelsen för Teknisk Utveckling

contract over Ahlstrom because it could demonstrate its MINO-process with the installation at Studsvik, while Ahlstrom had encountered several technical problems during the commissioning of the plant in Värnamo. The project was, however, never realised. In 1997-1998, the activities in the project ceased before plant construction had begun and in 2004, the whole project was aborted since the Brazilian energy market did not fulfil the formal conditions of the World Bank (Rensfelt, 2008; Waldheim, 2010).

However, the interest in atmospheric BIGCC in Europe had picked up and a call for proposals came in July 1993 within the context of the 5th EC Framework Programme (*resource mobilisation*). The call targeted the construction of three semi-commercial BIGCC plants at a scale of 8-12MW_{th} based on short rotation coppice (SRC). TPS, in collaboration with three other European partners, was selected in July 1994 for what has become known as the Arbre project (*knowledge development, entrepreneurial experimentation, materialisation, market formation*) (Rensfelt et al., 2003).[202] The plant was completed, commissioned and operated as a complete unit only for a few hours before being shut down (see Rensfelt et al. (2003) and Piterou et al. (2008) for an analysis of the project). By the end of this episode all BIGCC demonstration projects had either failed or been terminated, not only in Sweden but all over the world.

In conclusion, due to the two nuclear accidents and a growing public distrust towards coal, the gasification of biomass was once again identified as a strategically important knowledge field by the government and the two dominant energy utilities. The utilities were, however, also the owners of the nuclear plants in Sweden and were more or less "forced" to start developing alternatives to nuclear energy.

In so doing, they did not have a national perspective on the development of a knowledge field of strategic importance. Instead of drawing upon and strengthening the structure of biomass gasification that had emerged during the previous episode, Vattenfall and Sydkraft chose to mostly strengthen the TIS of biomass gasification in Finland. Their actions

[202] They later also received an NFFO contract, which in Britain would guarantee them a fixed price of 8.75p/kWh for electricity over the next 15 years. The technology was based on the TPS atmospheric CFB gasifier, from which producer gas, after gas cleaning and compression, was discharged in a Typhoon 4.5MW gas turbine (Rensfelt et al., 2003).

strengthened the functions of *knowledge development*, *entrepreneurial experimentation*, *materialisation,* and *market formation*. By strengthening the *know-how* of the actor structure—consisting of VTT, Ahlstrom and Carbona—the capacity to actually make further advancements based on the new science and technology infrastructure was also created, again mostly in Finland (see Chapter VIII). One can argue that some of these functions were also strengthened in Sweden (especially *materialisation* with the construction of the Värnamo facility), but there is little value in having a technology structure without an actor structure.

Since the actor structure consisting of TPS and Götaverken was not selected, TPS was forced to seek collaboration outside Sweden to maintain and advance its know-how of constructing gasification plants. As a result, the gasification competence at TPS managed to survive until new possibilities emerged in Sweden around 2000. Götaverken, which was acquired by Kvaerner, ceased its activities in FB gasification altogether.

7.1.3 Episode III: 1995–2009. The re-emergence of alternative fuels

The third episode emerged during the end of the 1990s, partly in parallel with the development of BIGCC. Once again, alternative fuels were part of the agenda. This time, however, *the direction of search* in favour of biomass gasification came from the desire to reduce particle emissions, abate climate change and "saving" the Värnamo plant from ruin.

This episode started with a debate over particle emissions from diesel vehicles, which cause urban air pollution and respiratory diseases (*direction of search*). The European response was the introduction of the Euro I standard in 1992, which set a limit on carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and diesel particle matters.[203] This first standard was subsequently followed up with more stringent ones, forcing engine manufacturers to make significant and costly investments to develop cleaner diesel engines. These standards also created incentives for engine manufacturers to begin experimenting with and developing alternative fuels as a means of reducing particle emissions (Röj, 2009).

[203] By 2008, and with the introduction of Euro V, diesel particle matters had been reduced by close to 97 percent and other emissions had been reduced as well.

In the 1990s, one such development was the introduction of natural gas vehicles in a number of cities around the world. However, even though natural gas reduces particle emissions, the engines do not enjoy the same thermal efficiency and robustness as diesel engines do. Using natural gas in heavy-duty vehicles is, therefore, not a preference among most engine manufacturers (Röj 2009).

In 1995, therefore, it was with great interest that Volvo AB read three papers written by Ammoco, Navistar and AVL, which illustrated the fact that particulate emissions could be completely eliminated and NO_x emissions reduced by 40 percent by running a diesel engine on Dimethyl Ether (DME). In addition, it was argued that the cost of operating a DME infrastructure would be on par with diesel (Fleisch and Meurer, 1995).[204]

The publications received significant attention, especially since they came from large, well-respected, incumbent actors (*knowledge development, legitimation and direction of search*) (Röj 2009). They also inspired Volvo to begin experimenting with the new diesel fuel. These experiments eventually materialised in a first-generation DME demonstration vehicle in 1999 (*entrepreneurial experimentation, materialisation*) (Röj, 2009).

Soon thereafter, Volvo's interest in DME encountered a corresponding interest in the municipality of Växjö, which had decided to become free from fossil fuels by 2020, as well as the interest of the Swedish Energy Agency in "saving" the Värnamo plant.[205] Interest in and around Värnamo, which is located in the municipality of Växjö, had grown in support of keeping and developing the competencies associated with the BIGCC demonstration plant that Sydkraft had been running during the 1990s but was now determined to sell.

The local interest in "saving" the demonstration plant from being sold was strongly supported by the Swedish Energy Agency. They considered that it would be "a shame" if the plant was sold, dismantled and shipped abroad (which Sydkraft was planning to do at the

[204] At the time, stranded natural gas fields were considered to be the main feed-stock for producing DME, and the reduction of CO_2 was not used as an argument for supporting DME (Röj, 2009). Coal was, however, viewed as controversial, and the benefits of biomass in producing DME had been identified and analysed (Blinge, 1994).

[205] The interest in alternative fuels based on domestic and renewable sources re-emerged with the climate change debate. It began to be taken seriously in the political arena towards the end of the 1990s (*direction of search*) (Sandén and Jonasson, 2005).

time), since they had spent SEK 150 million of the government's money to construct it (Tegnér, 2009).[206]

Sydkraft had offered the Swedish Energy Agency the plant for as little as SEK 1 (approximately €0.1), but the agency had to decline since they are not allowed to own such facilities (Levald 2009; Tegnér, 2009). At the time, TPS re-entered the Swedish gasification field. Together with Volvo, they became the main agents behind the creation of a consortium of mostly Swedish companies with a common interest in investigating the possibilities of reconstructing the Värnamo facility for the demonstration of DME production from biomass, and to test and verify the use of DME as a motor fuel (Atrax Energi, 2002; Danielsson, 2008).[207]

In 2002, the investigation concluded that it would cost about SEK 540 million (€54 million) to rebuild and demonstrate DME production from biomass at the Värnamo facility.[208] Mr. Danielsson at Volvo AB, who was the project leader for the Bio-DME project, tried to convince the large incumbent mineral oil companies to invest major sums of money for the further development of the technology. However, beyond putting up a few hundred thousand krona for the Bio-DME project, Mr. Danielsson (2008) described their interest in the technology as "ice-cold".

Volvo's own interest also dissipated when faced with the large sums of money required to further develop the technology. It could not see fuel production as part of its core business in the future. In addition, it had discovered that the engine development required to realise mass production of DME vehicles was not easily achieved. The adoption of the fuel injection system that was needed was more difficult than first anticipated, and further development of the technology would generate larger costs than Volvo was prepared to invest at the time

[206] When Ann Segerborg-Fick started her career at the Energy Agency in 2000, and later became responsible for the Värnamo project, it was all about "saving the Värnamo plant" from being shipped abroad (Segerborg-Fick, 2008).

[207] The study was financed by the consortium, where each member paid a small amount that was, in turn, matched by the Swedish Energy Agency (*knowledge development and resource mobilisation*) (Danielsson, 2008).

[208] It was also concluded that a greenfield production plant, with a capacity of 200,000 tonnes of DME from biomass per year, would cost about €390 million to build. The production cost of the DME from such a plant was estimated to be €0.49-0.55 per litre diesel equivalent (Atrax Energi, 2002).

(Röj, 2009).[209] As a result, the project to reconstruct Värnamo for DME production became mostly viewed as a research project rather than a commercial project. It would thus require large subsides from the government and the EU in order to be realised.

Two parallel research initiatives with alternative motives were initiated as a response to Sydkraft's move to sell the plant. The first came from the Greek company Helector, which was in the business of waste incineration and was interested in developing the Värnamo facility for demonstrating refuse-derived fuel (RDF) gasification. A contract was signed between Helector and the European Commission within the context of the 5th Framework Programme and aimed at further demonstrating the IGCC operation at Värnamo (*resource mobilisation*) (Ståhl et al., 2004; Ståhl, 2008).[210]

The second initiative came from some of the partners behind the DME consortium, TPS and Ducente AB being among them.[211] They applied to the European Commission, to a call for proposals within the 6th Framework Programme, for the demonstration of a hydrogen-rich synthetic gas from renewable feed-stocks such as biomass. The research project, which has since become known as CHRISGAS, would not cover the actual reconstruction of the Värnamo facility, but research at the facility once it had been reconstructed (CHRISGAS, 2003; Ståhl, 2010).

The Swedish Energy Agency had already expressed its explicit desire to "save" the Värnamo plant. It therefore supported the CHRISGAS application and wanted to take part in funding the necessary reconstruction of the plant (Tegnér, 2009).[212] The Swedish Energy Agency granted SEK 75 million (€7.5 million) to Växjö University in 2004 on condition that the CHRISGAS project would be granted (*resource mobilisation*).

[209] Motor development was able to progress in the context of the AFFORHD (Alternative Fuel For Heavy Duty) project, financed by the 5th EU Framework Programme. Within the time frame of the project (2002–2005), the second-generation fuel injection system for DME and the drive-train were developed and demonstrated. At the end of period, the goal was to have one heavy-duty vehicle rebuilt and optimised for DME and ready for field testing (Landälv, 2005).

[210] A third option had also been discussed, which was to sell the plant to Helector and ship it to Greece (Ståhl, 2008).

[211] Ducente AB is a consulting company founded by the former project leader of Värnamo BIGCC from Sydkraft, Krister Ståhl.

[212] The willingness to co-finance the project was also clearly expressed in the application to the EC (CHRISGAS, 2003).

With this decision, EUN (the deciding board at the Swedish Energy Agency), made it clear that the Värnamo project was underfinanced (EUN, 2004).[213] EUN had by then been presented with a preliminary total budget which indicated that the reconstruction of the plant and the demonstration of syngas production would cost approximately SEK 450 million (€45 million) (Waldheim and Ståhl, 2006).[214] If an additional application to the ERA programme[215] and partner financing would be granted, the total financing required by the Swedish Energy Agency was SEK 258 million (€26 million). It could, therefore, be expected to commit at least SEK 183 million (€18 million) in the following years for the reconstruction of the plant.

When the CHRISGAS application was eventually granted (€9 million), a new company called Värnamo Växjö Biomass Gasification Centre (VVBGC) was created. It became a subsidiary to the holding company of Växjö University with the purpose of owning the Värnamo plant, leading its reconstruction and coordinating the CHRISGAS project. The plant was eventually sold to VVBGC for SEK 4 million (€0.4 million).[216]

However, for the CHRISGAS application to be approved, the European Commission demanded that an IPR agreement be established (Bengtsson, 2008). The purpose of the IPR agreement was to avoid future conflicts between CHRISGAS partners and the original owners of the plant (Foster Wheeler and Sydkraft), who owned the pressurised gasification technology through the company Bioflow.

The majority owner of Bioflow, Foster Wheeler, had no interest in granting VVBGC more than a limited right to use, improve and sub-licence the technology to the CHRISGAS

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[213] If the EU was to approve the CHRISGAS project, the Swedish Energy Agency would have to commit substantial resources to the project in the future, which would decrease its ability to finance other research and development programmes in the future (EUN, 2004).

[214] The CHRISGAS project and the reconstruction of the Värnamo facility did not include DME or any other actual production of synthetic fuels.

[215] The ERA program is a European Commission funding scheme with the purpose of stepping " ... up the cooperation and coordination of research activities carried out at national or regional level in the Member States and Associated States through: the networking of research activities conducted at national or regional level, and the mutual opening of national and regional research programmes." Source: http://cordis.europa.eu/coordination/era-net.htm, Accessed 2010-06-22.

[216] The vision behind the creation of VVBGC was a European centre for research and development concerning gasification of renewable energy carriers (i.e., biomass) and the subsequent syngas processing (VVBGC, 2006; Bengtsson, 2008).

partners (see Chapter VIII).[217] The primary objective of the IPR agreement was to satisfy the EC and enable reconstruction and future research at the plant at the lowest possible cost. Limited rights were therefore deemed to be sufficient for these purposes, and these were later acquired from Bioflow by VVBGC for SEK 3 million (VVBGC, 2006; Bengtsson, 2008).[218] Hence, the future commercialisation of the technology was not in focus when the IPR agreement was signed. According to VVBGC, it was not their responsibility to take on future commercial gasification projects, but up to the various CHRISGAS partners instead (Bengtsson, 2008).

TPS was identified by both VVBGC and the Swedish Energy Agency as the main CHRISGAS partner for taking on such projects (Bengtsson, 2008; Segerborg-Fick, 2008; Tegnér, 2009). Despite being a relatively small company, TPS was seen to have the required competencies for leveraging the knowledge developed within the CHRISGAS project and taking on future commercial projects. TPS also had the proprietary rights to the pressurised BFB gasification technology developed in the 1970s and 1980s. Hence, even if it was the Foster Wheeler CFB gasifier that would be demonstrated at the Värnamo facility, the resulting commercial plants could be based on TPS technology and know-how (Bengtsson, 2008; Rensfelt, 2008). In addition, Talloil AB had acquired TPS in 2004 and was considered to be a financially strong and credible owner (Bengtsson, 2008; Talloil, 2004; TPS, 2004).

As a result, at the outset of the project everything looked quite promising. An actor structure with the required competencies and financial muscles were in place. The project was backed by the EU and the Swedish Energy Agency and had stronger national ties than did those in the previous episode. The technology development would, therefore, strengthen the Swedish actor structure and hopefully lay the foundation for a future national industry.

However, by spring of 2005 problems began emerging when the WASTE project was terminated, and Helector declared that it no longer was interested in the project. The

[217] According to the "Agreement on Transfer of Know-How and License Rights", improvements of the Bioflow technology at the Värnamo plant would be allowed as long as Bioflow was informed about the changes and the rights to the improvements were transferred to them. VVBGC could only sub-license the rights to the technology to the CHRISGAS partners but was allowed to make use of the technology outside the CHRIGAS project against further compensation—a royalty that is specified in the agreement—to Bioflow (MAQS Law Firm, 2008).

[218] The IPR agreement was approved by the Swedish Energy Agency, who had taken part in the negotiations, the CHRISGAS partners and the European Commission (Segerborg-Fick, 2008; Bengtsson, 2010).

original idea had been that the WASTE project would refurbish and restart the plant for IGCC operation. The plant would then be up and running and the necessary personnel trained when VVBGC and the CHRISGAS project would take over in 2006-2007 (Bengtsson, 2008; Segerborg-Fick, 2008; Ståhl, 2008; Tegnér, 2009). The lack of interest from Helector and Sydkraft to support the project may very well have been due to a mutual lack of interest from VVBGC to actually host the WASTE project at the Värnamo plant (Gårdemark, 2009; Ståhl, 2010).[219,220]

In addition, the ERA application for SEK 45 million (€4.5 million) was rejected and local companies in Växjö, which had promised an additional SEK 5 million (€0.5 million), failed to pay up (Waldheim and Ståhl, 2006). Consequently, the need for funds for realising the reconstruction of the Värnamo plant increased and when VVBGC applied to the Energy Agency, in April 2006, they asked for SEK 250 million (€25 million) instead of the expected SEK 183 million (€18 million) for completing the reconstruction of the Värnamo facility (VVBGC, 2006).

As a response, the director of the Department of Energy Technologies at the Swedish Energy Agency, Birgitta Palmberger, sent a formal letter by e-mail to the principal of Växjö University, Johan Sterte, in which she explained that the application exceeded the expected SEK 183 million (€18 million) by 40 percent. The new sum, SEK 250 million (€25 million), had not been accounted for in the Swedish Energy Agency's current budget; as such, supporting the application was deemed impossible without further inquiry. She stated in her e-mail [my translation]:

"We need to secure the ability to commercialise the results from the projects and it would thus be of great advantage if the companies already now invest in some sort of ownership."[221] (Palmberger, 2006).

The Swedish Energy Agency appointed an international group of experts to assist in the decision-making process.[222] The experts concluded that the CHRISGAS project and the

[219] The engineers at VVBGC were worried that RDF gasification would damage their plant (Gårdemark, 2009).
[220] Since electricty production no longer was in focus the project was not aligned with the interests of Sydkraft, which also exited the TIS.
[221] Original text: "vi behöver också säkerställa möjligheten att kommersialisera resultaten från projektet och ser därför en stor fördel om företagen redan nu går in i någon form av ägarskap." (Palmberger, 2006).

Värnamo plant provided an excellent opportunity to demonstrate the technology, but that the project is too research-oriented to make the technology commercially interesting for the future. They suggested that:

" ...the project needs a clearly defined industrial strategy, which the evaluation team believes can come via strong industrial leadership." (Junker et al., 2006, p.4).

In line with the letter sent by Mrs. Palmberger and the advice from the expert group, EUN decided to grant SEK 182 million (€18 million) to VVBGC on condition that a group of industry representatives financed the remaining SEK 68 million (€6.8 million) (Energimyndigheten, 2006b). The industry group was required to form a new company (Company A), which would have direct influence over VVBGC, proprietary access to the knowledge generated at the Värnamo plant, and be responsible for the future commercialisation of the technology. The new demand by the Swedish Energy Agency was clearly triggered by rising costs. It also marked a shift in its view on the commercialisation process from being very loosely defined to having specific responsibilities assigned to a core group of actors.

In autumn 2006, the ability to secure a group of firms to invest in Company A looked very promising. TPS and Talloil decided that they wanted to lead the effort, and the gas company AGA and venture capital firm Industrifonden were also seriously interested (Bengtsson, 2008; Rensfelt, 2008). An initial potential customer, Göteborg Energy, was also interested in constructing the first commercial-scale plant (see box 7.1) (Junker et al., 2006; Gunnarsson, 2009).[223]

However, these prospects quickly changed. The IPR contract that had been signed between VVBGC and Bioflow was brought up for investigation (Bengtsson, 2008). While the contract had been "good enough" to satisfy the European Commission and the Swedish Energy Agency in the context of the previous, loosely defined commercialisation process, it was far

[222] The experts were: Helle Junker from DONG Energy, Eric D. Larsson from Princeton University, and Hartmut Spliethoff from Munich Technical University.
[223] Göteborg Energy had already decided to build a 100MW biomass gasification plant for BioSNG production. However, they ultimately chose not to participate due to what they considered was the high cost associated with running the demonstration plant and the fact that there were no commercial actors at the time willing to supply a commercial plant based on the Värnamo technology within the suggested time horizon (Gunnarsson, 2009; Hedenstedt, 2009).

from “good enough” to satisfy potential industrial partners to invest SEK 68 million in Company A and assume control of the commercialisation process, which the Swedish Energy Agency was now demanding.[224]

Further problems emerged soon thereafter. In less than two years, Talloil had managed to turn profits into major losses and both Talloil and TPS were forced into reconstruction. In September 2007, TPS was sold to a venture capital firm—ACAP Invest AB—that had little interest in Company A (Talloil, 2006; TPS, 2007). With TPS and Talloil out of the picture, there were no alternate actors capable of appropriating the benefits of the necessary technology development and to take on future commercial projects. TPS had been the only Swedish company with experience from FB gasification from the previous episodes and still active in the field.

As a result, in December 2007, the Swedish Energy Agency decided to mothball the project and freeze all current payments to VVBGC until further notice. The project is, however, still alive. Erik Rensfelt, with whom gasification pretty much started in Sweden in the 1970s,[225] has been appointed as a new CEO of VVBGC. The Swedish Energy Agency defined Mr. Rensfelt’s new mission as solving the IPR situation and finding new industrial partners willing to create Company A (Energimyndigheten, 2007; Rensfelt, 2008). As of May 2010, he was still working to complete this mission.

[224] The problem with the IPR agreement was that it did not clearly define the extent of Bioflow’s future rights to further developments. Thus, it was not obvious how the agreement should be interpreted, which created uncertainty around the size of future royalties to Bioflow and the actual potential to appropriate the benefits of the technology developments. In retrospect, it would have been better if no agreement had been written at all, since all patents for the technology had expired. However, an agreement was required by the EC (Bengtsson, 2008; Rensfelt, 2008).

[225] When he received the broad mission from Norrlandsfonden “to do something interesting with peat”.

Box 7.1: System building activities undertaken by Göteborg Energy

Natural gas has always been a controversial issue in Sweden, and has suffered from a lack of legitimacy. Despite ambitious plans for a nationwide grid, natural gas is currently only available in the southern and western parts of Sweden. Until more recently, it has not been used for electricity production since the electricity sector has been dominated by nuclear and hydro power. For heating purposes, biomass and electricity have been the preferred choices. In addition, since the introduction of a CO_2 tax in 1991, the use of natural gas for energy purposes has not been favoured (Hellsmark, 2005).

However, a window of opportunity opened when the nuclear reactors at Barsebäck were de-commissioned in 2005. In coalition with E.ON and others, Göteborg Energy worked to change the existing tax rules. These efforts were successful and allowed Göteborg Energy to build a 600MW NGCC in Göteborg (Hellsmark, 2005). However, with its large-scale investment in a fossil resource plant, Göteborg Energy was under political pressure to further develop biogas as an alternative. During a meeting between the Green Party and the management of Göteborg Energy with regard to the allocation of emission rights of the NGCC, Göteborg Energy was asked whether they could do something to increase the production of biogas in Sweden (Hedenstedt, 2009).

In response, Göteborg Energy hired the consultancy firm Nykomb Synergetics to conduct a preliminary study on the technical possibilities for large-scale BioSNG production. The study pointed in two directions: either further develop the pressurised fluidised bed technology that had been demonstrated in Värnamo, or further develop the FICFB gasification processes being demonstrated in Güssing (see Chapter V) (Hedenstedt, 2009).

The CEO (Mr. Hedenstedt) and the utility's management group decided that they should start preparing for the construction of a commercial plant of 100MW to produce BioSNG based on the gasification of forest residues. Consequently, a project group and a new subsidiary called Gobigas were created. The task of the project group was to realise this vision as soon as possible (Hedenstedt, 2009; Gunnarsson, 2009).

The project group spent most of 2006 making the necessary preparations for issuing a tender to possible technology suppliers of such a plant. During their preparations, they regarded the pressurised FB technology of Foster Wheeler as the most interesting option. However, TPS and Foster Wheeler were either unwilling or unable to make an offer for the desired plant within the specified time frame. As a matter of fact, most of the incumbent actors with the potential to develop the BioSNG application based on biomass gasification declined to make an offer to construct such a plant. Since neither TPS nor Foster Wheeler were interested, Göteborg Energy could see no reasons for further engaging the Värnamo project and Company A (Hedenstedt, 2009; Gunnarsson, 2009).

However, a new option that also reduced interest in participating in the Värnamo project had emerged during the process. A researcher at Chalmers, Henrik Thunman, was asked to look into the question of how large-scale BioSNG production could be accomplished in Göteborg (Thunman 2009). He had a longstanding relationship with Professor Hofbauer at TU Vienna and knew that the FICFB Güssing plant worked very well. By simplifying the existing design, he came up with a way of retrofitting existing CFB combustion plants with a gasification, thereby reducing the cost of building FICFB plants in the future (*knowledge development*) (Thunman, 2009).

With the financial help of Göteborg Energy, the 20-year-old 12MW CFB boiler at Chalmers University was retrofitted with a gasification unit of 2-4MW fuel power. The cost of the project was SEK 12 million and the demonstration was successfully inaugurated in December 2007 (*knowledge development, resource mobilisation, entrepreneurial experimentation, materialisation*) (Thunman, 2009).

At the plant, since the product gas is re-circulated into the boiler, the demonstration carries its own operating costs, and research can be simultaneously undertaken on the gasifier and on gas based on slipstreams. This significantly reduces the cost of research compared to the Värnamo set-up. Since construction, the project has received further financial support from the Swedish Energy Agency (SEK 17.7 million), and Metso Power has entered the TIS in Sweden by supporting the technology development with an additional SEK 10 million (Energimyndigheten, 2009a; Chalmers, 2009).

While developing the demonstration facility at Chalmers, Göteborg Energy eventually managed to secure three offers from technology suppliers for a 100MW plant in Göteborg for BioSNG production. It chosen to proceed with the offer from an alliance headed by Repotec (see Chapter V), which proposed a three-stage solution where an initial 20MW BioSNG plant will be constructed once the 1MW metanisation unit in Austria has been demonstrated. When completed, it will be followed by a subsequent scale-up of the technology with two 40MW plants. The cost of the first stage has been estimated to be SEK 700 million (€70 million), and the total investment as approximately SEK 2,500 million (€250 million) (Gunnarsson 2009). The Swedish Energy Agency has decided to support the project with SEK 222 million (€22 million), and Metso Power and E.ON have entered the alliance (Energimyndigheten, 2009c; Gunnarsson, 2009).

Based on the estimates made by Göteborg Energy, the gas from such a plant should be competitive with natural gas and biogas as long as it is used as a vehicle fuel. However, to secure the long-term legitimacy of using BioSNG as a transportation fuel, Göteborg Energy has recognised the need to form a strategic alliance with the automakers to advance engine development. Improved engines have been identified as important for achieving the same high level of fuel efficiency and robustness shown by existing diesel engines (cf. ZSW in Chapter VI). However, actors such as Volvo AB or Volvo Cars have been hesitant in their support of the project to date (Röj, 2009).

7.1.4 Summary of Episodes I-III: The evolution of fluidised bed gasification in Sweden

During the third episode, the possibilities of creating a national industry capable of realising the potential of FB gasification based on the Värnamo facility deteriorated further, for a number of reasons that will now be summarised.

In the first episode, a world-leading actor and technology structure was created in Sweden. It was based on pressurised fluidised bed gasification and the commercial-scale atmospheric CFB gasification for oil substitution in lime kilns. During the second episode, interest in developing a substitute for oil disappeared, and new actors entered the TIS to develop the technology for large-scale electricity production. However, the two main actors, Sydkraft and

Vattenfall, chose not to strengthen the actor and technology structure that had already been created. Instead, the main activities undertaken to strengthen the know-how and industrial capacity to build such future plants strengthened the actor structure in Finland, consisting of VTT, Foster Wheeler and Carbona (see Chapter VIII). A critical aspect of this was that the knowledge and control over the Värnamo facility was "given" to Foster Wheeler. The main actors from the first episode, Götaverken and TPS (Studsvik), were thus not selected by Vattenfall and Sydkraft. TPS was instead supported by a number of municipal companies that were interested in TPS smaller scale, atmospheric BIGCC technology, which was more suitable for the district heating systems owned by these utilities. However, policy was not willing to support demonstration project with 50 percent funding or more, which was argued to be necessary to offload the technical risk of investing in the technology. Consequently, TPS was forced to survive until the third episode through having contracts abroad.

When new incentives to develop alternative transportation fuel based on biomass gasification emerged, an alliance was formed consisting of TPS, Volvo, the Swedish Energy Agency, and some local firms around the Värnamo facility. The alliance had a common interest in "saving" the Värnamo facility and in demonstrating the production of an ultra-clean syngas suitable for DME production or other synthetic fuels. In addition, a local utility, Göteborg Energy, expressed an interest in acquiring such a commercial-scale plant.

The alliance was almost able to mobilise the necessary resources and competencies for rebuilding the plant, but ultimately failed—not because of lack of will or competence, but due to a number of circumstances outside its control. First, the alliance did not own the IPR rights to the Värnamo plant. The real owner, Foster Wheeler, had no incentive to support the alliance and or grant it a technology license sufficient for enabling the creation of Company A.

Second, the cost of reconstructing the plant was high and perhaps too high for the alliance. The size, location and infrastructure of the plant had been determined based on the minimum size of the available gas turbines. The options for reducing investment costs by building a smaller demonstration or running it in a continuous mode for electricity production (or finding other ways to cover at least the operating cost the plant) were extremely limited due to previous choices. The cost of research at the plant would, therefore, be relatively high. These high costs also partly discouraged Göteborg Energy from investing in Company A.

Third, the final "nail in the coffin" proved to be the financial problems created by the owner of TPS, Talloil. With TPS out of the picture, there was no longer any Swedish-based actor structure that could capitalise on the completion of the Värnamo plant for syngas production. These problems have thus resulted in an altogether weaker Swedish actor structure.

Nevertheless, the project lives on and hopes for its eventual success come down to one individual, Erik Rensfelt, who must solve the IPR situation and create a new alliance with an interest in commercialising biomass gasification based on demonstrating the technology at the Värnamo facility. Meanwhile, an alternative alliance of actors has been formed by Göteborg Energy. Together with E.ON, Chalmers, Metso Power, and Repotec, it has constructed a demonstration facility at Chalmers and is in the process of building an initial large-scale 20MW BioSNG facility.

7.2 Three episodes of entrained flow gasification in Sweden, 1978–2008

The second major trajectory in Sweden concerns black liquor gasification, which has its origins in the late-1970s and in the gasification of extra-heavy oils, bitumen and coal for methanol and ammonia production. The history of black liquor gasification (BLG) can be divided into roughly the same three main episodes as outlined above. The first episode began in 1978 with the second oil crisis and ended in 1986. In this episode, an initial technology and actor structure emerged in terms of a patent on black liquor gasification and the two important companies for the further development—Chemrec and Nykomb Synergetics. The second episode focuses on Chemrec's efforts to turn invention into innovation for the production of heat and electricity through an IGCC integrated in the pulp and paper industry. During the third episode, interest in using the technology for electricity production vanished but was instead replaced by strong *direction of search* for the production of transportation fuels.

7.2.1 Episode I: 1978–1986. Kombinat Nynäs and the creation of a structure

The first episode began in 1978 in the town of Nynäshamn about 60km from Stockholm, where Nynäs Petroleum AB operated an oil refinery and had its headquarters. Nynäs Petroleum identified a potential business during the second oil crisis (*direction of search*): developing their refinery operations by integrating a gasification process for coal, extra-heavy oils and bitumen within the existing refinery structure. This concept (*knowledge development*) offered reduced dependency on conventional oil and the introduction of a flexible combination for the production of heat, electricity and methanol (NE, 1981:6).[226]

There were many factors in favour of the project, which was commonly known as Kombinat Nynäs. The main actor of the project, Nynäs Petroleum AB, had very good preconditions in place for production. It had the necessary competencies, access to infrastructure and a conventional refinery in Nynäshamn into which the gasification complex could be integrated. Integration was argued to result in improved economics and environmental performance of both the existing refinery and the future gasification plant (Schein, 1990).

Nynäs Petroleum was able to mobilise support and resources (*resource mobilisation*) from an alliance of actors supporting the project, consisting of Svensk Metanolutveckling AB (Swedish Methanol Development) (SMAB), Sydkraft AB, 'Stockholms Energiverk' (Stockholm Energy) and Södertörns Fjärrvärme (Södertörns District Heating). The alliance developed a proposal for a large-scale facility which was presented for the "Nämnden för energiproduktionsforskning" (Swedish Energy Board).[227] It eventually supported the idea of a plant with the capacity to produce 700,000 tonnes of methanol and a combined heat and power production equivalent to 600MW_{th} (NE, 1981:6). The alliance expected the plant to be in operation by 1987.

However, loud protests were voiced when the plans for building a coal and oil gasification plant in Nynäshamn were presented to the public. Coal was not considered legitimate for environmental reasons and the protestors managed to renegotiate and delay the entire

[226] Methanol was viewed as the best alternative fuel to petroleum at the time (DFE, 1982).
[227] This alliance was most temporary and other actors also entred and exited as the project was developed (Landälv, 2010)

project. While a new configuration that excluded the use of coal was presented in 1986, the price of oil suddenly dropped, making methanol less attractive to produce (Schein, 1990).

The plan for a gasification plant in Nynäshamn was, however, not terminated. Instead, the advocates came up with a new configuration that could be profitable. This time, the actors saw a potential business in the production of ammonia for fertilisers. Ammonia production uses a similar synthesis process as methanol, but demands more electricity. The plan was finally approved by the government under the condition that enough electricity would be produced to cover internal demand. Such a production was, however, still too small to motivate the additional investment cost. Instead, electricity production had to be scaled up and the surplus electricity and heat was to be sold on the market (Schein, 1990).

At the same time, a new competitor for the attractive heat market in Stockholm had emerged. A commercial demonstration project with a new coal combustion technology[228] was suggested to be built at Värtan, in central Stockholm. The technology had been developed by ASEA, and had the full support of Vattenfall as well as the government, which saw the potential of an export market for ASEA (Jacobsson, 1994).[229]

In competition with ASEA, Nynäs Petroleum drew the shortest straw. Vattenfall and Stockholm Energy, which controlled the electricity and heat market, did not select the project and refused to sign a long-term contract with Nynäs Petroleum. Project advocates argued that the price they could offer was competitive with other alternatives at the time, but that Vattenfall and Stockholm Energy had other priorities (Ruberg 2009, Schein 1990).[230]

Although the Kombinat Nynäs never materialised, it became the first *entrepreneurial experiment* with high temperature gasification in Sweden. A series of positive and mutually re-enforcing events strengthened the functions of *resource mobilisation, entrepreneurial*

[228] Pressurised fluidised bed combustion based on pulverised coal (Jacobsson, 1994)

[229] Vattenfall and ASEA have a common history of developing technology together. They thus share a common understanding of which technologies are relevant and how things should be done (cf. "den gemensamma utvecklingen" (Fridlund, 1999). Nynäs Petroleum has never been part of this common development, and since the gasification technology was new to Vattenfall and never really been pursued by ASEA, as it was viewed with scepticism (Schein, 1990). The PFBC Värtan project also failed for numerous reasons, see Jacobsson (1994) for a review.

[230] Mr. Rudberg (2008) speculates that the primary reason for terminating the project is that Vattenfall did not want a competitive alternative to nuclear power on the market.

experimentation and *knowledge development,* and resulted in a new actor and technology structure. This new structure would prove to be very important for the future development of black liquor gasification for three main reasons.

First, it resulted in the creation of a new actor, Nykomb Synergetics, which was founded by Nynäs Petroleum and the venture capital firm Investeringsbanken in 1986 to make all of the necessary technical and economical evaluations within the project. The idea behind the company was also to appropriate on the knowledge developed in the project and to consult other actors on the construction of similar projects elsewhere in the world (Nykomb, 2006; Ekbom, 2007).[231]

Second, an extended network of actors was created with knowledge and experience with in high temperature gasification. Third, a new gasification process was patented. The director of the project in Nynäshamn in its early phase, Jan-Erik Kignell, had background in the pulp and paper industry and could therefore recognise the similarities between the black liquor combusted in a chemical pulp and paper mill and heavy fuel oil (Rudberg, 2008). He believed that gasification could result in more efficient chemical recovery and that more electricity could be produced compared to a conventional recovery boiler. He presented this idea to Nynäs management, who were supportive of the idea but had their mind set on coal and oil gasification and did not want to explore the potential of black liquor gasification (Rudberg, 2008). Instead of pursuing the idea himself, Mr. Kignell filed a US patent on the idea in 1986 and sold it to a newly formed company called Chemrec (Kignell, 1989). Chemrec had been working on a similar idea but with a different technology (Bergek, 2002).

The remaining two episodes will concern the efforts undertaken by Chemrec to commercialise the technology invented by Mr. Kignell, first for electricity production and then for the production of alternative fuels.

[231] It was hired for the construction of two similar plants in Italy and has been working on numerous gasification projects around the world (Nykomb, 2006; Ekbom, 2007).

7.2.2 Episode II: 1986–1999. Black liquor gasification for electricity production

Due to a rapidly decreasing price of oil and the Chernobyl nuclear accident, the *direction of search* in this episode shifted from oil substitution to developing renewable technologies with the potential of replacing nuclear power (see Chapter 7.1.2 for a longer discussion).

The two owners of Chemrec, Mr. Stigsson and Mr. Bernhard, had previously been working at SKF Steel in Hovfors on a similar technology developed for the pulp and paper manufacturer STORA (Bergek, 2002).[232] When SKF and Stora declared that they were no longer interested in developing the technology, the two inventors formed Chemrec, started looking for new partners, and acquired the patent from Mr. Kignell.

By 1990, they had developed a synthesis of the two technologies with the goal of replacing the existing boilers for chemical recovery with the black liquor gasifier. They argued that it would result in more efficient chemical recovery and the production of nearly twice as much electricity. Hence, with a gradual shift towards the new technology, a significant amount of renewable electricity could be produced. As such the technology was viewed as an interesting option for replacing nuclear power (Hylander, 2002).

Shortly thereafter, Chemrec was acquired by the Norwegian company Kvaerner, which already owned the boiler manufacturer Götaverken and had a business selling recovery boilers to the pulp and paper industry. In 1991, Chemrec and Kvaerner managed to secure a loan of SEK 13 million (€1.3 million) from Industrifonden (*resource mobilisation*) for an initial demonstration of the technology (*entrepreneurial experimentation*). Together with the pulp and paper company Assi-Domän, they built an atmospheric "Booster" demonstration at the pulp and paper mill in Frövi (*materialisation*). The total investment for demonstrating the Booster was SEK 30 million (€3 million), and the facility had a capacity of 75 tonnes of black liquor solids per day (tbd) (Hylander, 2002).

The atmospheric application was viewed as a less advanced process than the pressurised one. It was not intended for electricity production, but for increasing the capacity and

[232] They had also constructed a pilot plant in 1985 that was later replaced by a new pilot plant at the same site in 1987, with a capacity of 3 tbd (*entrepreneurial experimentation*).

lifetime of conventional recovery boilers. Since it did not replace the existing recovery boiler, it implied less risk for the customer and was thus viewed as an application closer to commercialisation, allowing Chemrec to develop the technology at a lower cost and risk (*knowledge development*).

In 1995, a commercial breakthrough came with the first sale of a Booster to Weyerhaeuser in New Bern, USA (*market formation*). The Booster came into operation in 1996 and had a capacity of 300tbd, or 15 percent of the mill's capacity (*materialisation*).

In parallel with the Booster plant in New Bern, a smaller pressurised pilot plant was constructed at the pulp and paper mill owned by STORA in Skoghall, Karlstad. The intention with the new plant was to take the next step towards the development of the IGCC application in which the recovery boilers would eventually be completely replaced with a system of significantly higher electrical efficiency. The pilot plant could be operated at up to 15 bars of pressure and had a capacity of 6tbd using air as oxidant (*knowledge development, entrepreneurial experimentation*, and *materialisation*) (Hylander, 2002; Landälv, 2010).

However, Chemrec and Kvaerner had significant problems with the technology. The refractory linings at the Booster plant in New Bern and the pilot plant did not last for very long. In New Bern, different materials were tested, but none of them lasted longer than 8-10 months, and incurred a replacement cost of up to $1 million and two to three weeks of downtime (Rudberg, 2008; Landälv, 2010).

Due to the problems Kvaerner experienced with the Chemrec technology, it contracted Nycomb Synergetics in 1996.[233] Nykomb was the only company with experience in high temperature gasification in Sweden due to their common history in the previous episode (Rudberg, 2008). Nykomb thus re-entered the TIS in Sweden after having worked mainly on projects abroad (Bergek, 2002; Nykomb, 2006).[234]

[233] Nycomb Synergetics was renamed to Nykomb Synergetics in the mid-1990s (Landälv, 2010).
[234] One important technical improvement was recommended by Nykomb and implemented in the Skoghall plant in 1996. The oxidant was changed from air to pure oxygen, a decision that was shown to be vital in the further development of the technology. The produced syngas became considerably more energy rich (no nitrogen from the air) and thus a more suitable gas turbine fuel. The capacity of the plant went from 6 to 10 tpd (Landälv, 2010).

Since 1995 and the construction of the pressurised pilot plant, Chemrec and Kvaerner had been in contact with the pulp and paper company AssiDomän, discussing a larger demonstration plant using the pressurised technology for electricity production. With the aid of Nykomb, several configurations, scales and two different sites of the plant were under discussion for several years. They finally agreed to build a pressurised BLG unit at AssiDomän's mill in Piteå.

The plant had to be relatively large in order to justify the use of gas turbines and for the extra capacity that was being planned for the Piteå mill. It was therefore designed for 500-550tbd, equal to about one quarter of the black liquor at the mill. This implied scaling up the pilot plant by more than 50 times (Bergek, 2002; Hylander, 2002).

Even though severe technical problems had been encountered at the facility in New Bern as well in the pilot plant, the partners appeared confident that the technology would work on a larger scale. A plan was, however, made for how the remaining technical uncertainties could be solved, which involved building a smaller pilot facility close to the large demonstration plant (Hylander, 2002; Rudberg, 2008).

In 1997, further steps towards realising the plans were taken by creating a joint venture company. The cost of the construction was estimated to be SEK 475 million (€47 million) and the government body FABEL was ready to finance the project with 50 percent of the required funding (SEK 237.5 million, or €24 million) (*resource mobilisation*). The remaining sum would be shared equally between the two partners AssiDomän and Kvaerner (Rudberg, 2008; Tegnér, 2009).

During 1998, however, AssiDomän and Kvaerner experienced financial problems and became concerned that the technical risk was too high for such a large investment. As a result, they decided to postpone the construction of the large IGCC demonstration plant and suggested that the remaining technical issues should be resolved in a larger pilot plant at AssiDomän's mill site in Piteå.[235] The financial situation for Kvaerner and AssiDomän was by

[235] The US based company Air Product, were also interested participating in the project by supplying the equipment for oxygen production. With the introduction of black liquor gasification, they identified the pulp and paper industry as an important market for oxygen (Landälv, 2010).

then referred to as the primary reasons for not supporting the new plan (Bergek, 2002; Hylander, 2002; Rudberg, 2008).

During 1999, the financial situation at Kvaerner became even worse and a leading consulting firm recommended they "cut all negative cash flow" (Rudberg, 2008). Since Chemrec was most definitely in a negative cash flow situation, Kvaerner started to look for new owners for the company.[236] When Kvaerner and AssiDomän broke up the alliance with Chemrec, the second episode of black liquor gasification was terminated.

During this episode, Chemrec, in collaboration with Kvaerner, Nykomb and various pulp and paper firms, managed to strengthen *knowledge development, entrepreneurial experimentation, materialisation,* and *market formation* by building pilot and demonstration facilities, as well as a commercial-scale plant for the Booster application. As a result, they had access to a science and technology infrastructure that enabled them to strengthen *knowledge development* and *entrepreneurial experimentation* even further. A motor of positive interconnections had developed and a new structure of firms, networks and technology had been developed by the end of the episode. Nevertheless, the real commercial breakthrough was postponed for the future. After Kvaerner and AssiDomän broke up the alliance, Chemrec was in real financial difficulties and was being forced to struggle harder than ever before in order to survive.

7.2.3 Episode III: 2000–2009. Black liquor gasification for transportation fuels

During the first part of the third episode, Chemrec was struggling to survive. However, Mr. Tegnér, the head of FABEL who had been responsible for granting the SEK 237.5 million (€24 million) to Chemrec, identified the Chemrec technology as very important, even though AssiDomän and Kvaerner backed out of the project. When FABEL was subsequently integrated into the Swedish Energy Agency and Mr. Tegnér received a position there, Chemrec was allowed to keep the grant (Rudberg, 2008; Tegnér, 2009). According to Tegnér (2009), the grant was approved as a "development plan" for Chemrec, meaning that it could

[236] Mr. Landälv has estimated (2005b) that Kvaerner invested approximately SEK 200 million in the development of the technology during the eight years they owned the company.

not be used for salaries, but could be used for equipment and construction so long as 50 percent of the money came from other sources.[237]

With the Agency's provision of long-term financing, by 2000 Chemrec's problems appeared to have been resolved. Kvaerner managed to sell 52 percent of its shares in Chemrec to the German-based capital goods supplier Babcock Borsig, and 24 percent to Nykomb Synergetics (Chemrec, 2000). With the acquisitions, Babcock Borsig and Nykomb Synergetics had committed to co-finance and construct the new pilot plant in Piteå by 2003 (Chemrec, 2000; Rudberg, 2008).[238]

The cost of the pilot plant was estimated to be SEK 70 million (€7 million); it would be pressurised up to 32 bars and able to process 20 tbd and use oxygen as oxidant. It would include a novel refractory lining design, a new main burner design, an improved system for gas and smelt separation, be engineered for continuous operation, and equipped for long-term material testing to resolve the final technical problems that had been identified during the previous episode (Chemrec, 2002, 2005).

However, several new problems emerged and the completion of the new pilot plant was delayed due to a series of both unfortunate and fortunate events. To start with, the new principal owner, Babcock, experienced financial difficulties in 2001, could not meet its obligations (Chemrec, 2002), and filed for bankruptcy in July 2002. Fortunately for Chemrec, however, the Director of Nykomb Synergetics, Stefan Jönsson, managed to acquire Babcock's shares in Chemrec before it declared insolvency and had its assets frozen. As a result, by the end of 2002, Nykomb owned 76 percent of Chemrec shares. In 2003, they acquired the remaining shares from Kvaerner to became the sole owners of the company (Rudberg, 2008; Tegnér, 2009).

[237] The SEK 237.5 million thus provided a long-term financing situation for Chemrec that is probably quite unique. By 2009, they had still not used all of these funds (Rudberg, 2008).

[238] In 1991, Babcok had acquired the GSP coal gasification technology that had been developed in the former East Germany at DBI (see Chapter VI). The GPS technology, which used a cooling screen, had been developed especially for brown coal slurries that, just like black liquor, were considered corrosive. Tests were made using black liquor in the GSP gasifier. The tests were inconclusive due to practical problems and Chemrec adopted no technical solutions from Babcook (Rudberg, 2008; Landälv, 2010).

The intentions of Nykomb Synergetics were, of course, honourable. Indeed, without the swift action of Mr. Jönsson, Chemrec would have been dragged into bankruptcy with Babcock. Nevertheless, Nykomb is a small, family-owned consulting company with limited means of taking over Babcock's role.

In the meantime, by 2001 the Booster plant in New Bern had to be closed down due to overwhelming technical difficulties (*legitimation*). Moreover, the technical advantage Chemrec had indentified, replacing conventional recovery boilers with black liquor gasification, had overtime become less interesting due to the development of more efficient recovery boilers (Modig, 2005; Landälv, 2010).[239] As a result, no potential customer was interested in the technology for large-scale power production (*market formation*, *direction of search* and *legitimation*).[240] Hence, the years between 2000 and 2003 marked a very low point for Chemrec and the survival of the company was uncertain (Rudberg, 2008).

However, it decided not to give up and started to think of alternative use of the gas. Chemrec soon realised that the gas was an excellent syngas and could be used for synthesising various chemical products, at a near competitive price with fossil alternatives. It would, however, be necessary to restore the energy balance in the pulp and paper mill by building additional combined heat and power capacity at the mill (Landälv, 2010). Chemrec filed a patent covering the production of syngas from black liquor for the purpose of producing transportation fuels and other chemicals in 2001 (Landälv and Lindblom, 2001).

In addition, a study published by Nykomb in 2003 illustrated that Chemrec's technology could be used to produce substantial volumes of methanol, or other second-generation transportation fuels, substituting up to 30 percent of the demand for transportation fuels in Sweden at a relatively low cost (Ekbom et al., 2003). The continued strategic importance of the Chemrec technology could, therefore, be confirmed (*legitimation*).

[239] When Chemrec started the development in the 1980s it could illustrate a possible electrical efficiency of 22 percent compared to conventional boilers with an efficiency of 7-8 percent. By 2001-2003, the leading suppliers started marketing recovery boilers with an electrical efficiency of approximately 16 percent. The additional investment cost and risk involved with new technology could not motivate a shift to black liquor IGCC (Landälv, 2010).

[240] In addition, just as for Värnamo during the end of the 1990s and early-2000s, interest in building new electricity capacity was very low due to the deregulation of the electricity market and the halt in the decommissioning of nuclear power, which was no longer viewed as such a pressing issue.

Chemrec was then able to mobilise a set of very important financial and technical resources that allowed it to continue. The mobilisation of these resources was made possible by the emergence of a new *direction of search* in support of the development of alternative transportation fuels.[241]

With the renewed importance of alternative fuels, Chemrec, Nykomb and the Swedish Energy Agency undertook a wide range of activities to strengthen Chemrec and take the necessary steps towards commercialisation. To begin with, the remaining technical problems with the ceramics had to be resolved, causing the problems at plant in New Bern, USA. The first steps towards resolving these were already taken in 1997 when collaboration was initiated between Chemrec, Weyerhaeuser and Oak Ridge National Laboratory. Over time, Oak Ridge became one of the most important partners for Chemrec in advancing the development of the technology (Landälv, 2010). With their experience in developing and designing ceramic tiles for heat shields in space shuttles, a new and durable ceramic refractory lining could be developed for black liquor gasification. This collaboration enabled the Booster in New Bern to be restarted with a new design in 2003, with significantly improved availability as a result (*knowledge development, entrepreneurial experimentation, materialisation*) (Chemrec, 2003; Rudberg, 2008).[242]

In addition, Chemrec and the Swedish Energy Agency worked with Professor Tore Berntsson at Chalmers University to include Annex XV: "Gasification of Black Liquor", in the OECD/IEA implementing agreement on advanced energy-related technologies for the pulp and paper industry (IEA, 2003; Rudberg, 2008). The agreement was important for gathering the remaining technology expertise in black liquor gasification and keep a technology development alive, which experienced great difficulties at the time (Landälv, 2010).

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[241] Just as for Värnamo, interest in developing alternative fuels emerged as a response to the threat of climate change.

[242] Mr. Rudberg (2008) emphasises the importance of the long-term financing Chemrec received from the Swedish Energy Agency and the good contacts it had with the agency as the principal reason for surviving. The Swedish Energy Agency and good contacts with the universities also made it possible to make further connections and extend its networks. It was thanks to the Agency that Chemrec had the opportunity to meet with the US ambassador in Sweden, Mr. Woods. It was also one of the top three on the list of companies Mr. Woods ranked as the most promising companies in field of renewable energy in Sweden. Chemrec also managed to make very good contacts with the governor of Michigan, Mrs. Granholm, who visited the plant in Piteå with Mr. Woods. Given the long-term cooperation with New Page, Chemrec also had good contacts at the US Department of Energy, which financed much of the technology development in the US.

The Swedish Energy Agency and Chemrec also acted to set up research programmes that complemented the large FABEL investment grant. The purpose of these programmes was to further knowledge development for black liquor gasification and enable more than 50 percent of the funding for the construction of the pilot plant. In the first period, from 2001 to 2003, two smaller programmes were initiated. In 2004, these programmes were replaced by a larger programme on black liquor gasification (BLG), and a new legal unit called BLG Programmet AB was created (Kempe and Henke, 2009; Tegnér, 2009).[243] This allowed the initiation of research at three universities and two institutes in Sweden (Gebart, 2008). The programme and the entry of the various universities and institutes were important for strengthening *knowledge development* of black liquor gasification. As a result, the actor structure of the TIS was strengthened and several new entrepreneurial experiments could be conducted. These activities have in turn further extended the design space of biomass gasification and strengthened the actor structure of the TIS (see Box 7.2).

Through the financial arrangements established by the BGL research programme, the 1997 FABEL grant, and equity financing from the owner of Chemrec, the new pilot plant was completed and inaugurated in February 2005 by the Swedish Minister of Energy, Mona Sahlin (*resource mobilisation, entrepreneurial experimentation, materialisation*) (ETC, 2005; Gebart, 2008).[244]

Hence, in just three to four years a very difficult situation for Chemrec had been turned into a great opportunity. By 2004, it had a commercial-sized Booster plant operating without technical problems in New Bern, a new pilot plant under construction, several new patents on the technology, as well as access to top class international and national research (Landälv, 2010). In addition, if the technology could be made operational on a large-scale, a worldwide billion dollar market for renewable fuels could be realised at a relatively low cost.

[243] The new legal unit was created to allow for more than 50 percent funding for the construction of the new pilot plant. It is owned by LtU (45%), UU (45%) and Chemrec (10%). It is also through BLG Programmet AB that all the money has been distributed to participating research organisations (Gebart, 2008; Rudberg, 2008).

[244] The first period, BLG I, 2004–2006, involved SEK 100 million, of which SEK 34 million was channelled to the construction, technical development and operation of the new pilot plant, not including the SEK 30.3 million that could be allocated from the FABEL programme. The second period, BLG II, 2007–2009, involved SEK 85 million (*resource mobilisation*) (Gebart, 2008; Rudberg, 2008).

Even so, Chemrec had great difficulties finding new investors for developing the commercial opportunity.

Between 2003 and 2006, the management of Chemrec visited more than 40 different venture capital firms. Only one showed any interest in the company: Vantage Point Venture Partners, a US-based venture capital firm.[245] The CEO of the firm, Mr. Bulkin, had a lot of experience from the refinery industry, and knew what gasification was and appreciated its potential. In December 2006, the firm invested $10 million (€8 million),[246] together with the Swedish venture firm Volvo Technology Transfer (*resource mobilisation*) (Rudberg, 2008).

The investment in Chemrec resulted in Volvo re-entering the TIS for biomass gasification, which it previously had left during the Värnamo project in 2002. The focus of Chemrec has been on developing black liquor gasification for methanol or DME synthesis and Volvo's interest has, all along, been for developing DME as an alternative fuel. Meanwhile, the technology for DME in heavy-duty vehicles had been developed in the EU-AHFORD programme (Landälv, 2005). When the EU project was completed, Volvo mobilised an additional SEK 62 million (€6 million) from the Swedish Energy Agency to develop the third generation of BioDME vehicles. The grant covered 50 percent of the development cost and the goal of the project was to demonstrate the technology in field trials of 30 vehicles by 2009 (Energimyndigheten, 2006a).

Following the venture capital investment, a new series of positive events would occur. In August 2007, the first potential customer, New Page, ordered a feasibility study worth $1.2 million (€0.96 million) on a large-scale semi-commercial plant for fuel production at its mill in Escanaba, Michigan. The study was later supported by the US Department of Energy with funding of $0.3 million (€0.24 million) (Granholm, 2007; DOE, 2008; Rudberg, 2008).

Shortly thereafter, in April 2008, a similar agreement was signed between Smurfit Kappa (formerly AssiDomän) and Chemrec for a semi-commercial production plant utilising one-

[245] Volvo Technology Transfer indicated an interest at an early stage but it did not want to become lead investor in the company. Mr. Rudberg (2008) felt that the majority of the venture capital firms displayed great ignorance of the technology and an inability to evaluate it (cf. Teppo (2006)).

[246] In 2006, the average rate was 0.8 Euro for 1 dollar. Source: http://www.oanda.com/currency/average, Accessed 2010-06-22.

third of the black liquor at the mill in Piteå, corresponding to 70,000 tonnes per year of DME (Chemrec, 2008a; Rudberg, 2008). The investment cost of the above-mentioned plants has been estimated at SEK 1,400 million (€140 million) in Piteå and approximately $220 million (€176 million) in Escanaba (Rudberg, 2008).

7.2.4 The future of black liquor gasification in Sweden

For investors to make actual investment decisions and for the market for black liquor gasification to be realised, two main sets of uncertainties must be reduced. The first set is associated with the technical and organisational aspects of large-scale production, distribution and the use of DME from black liquor gasification.

The first major step to reduce these uncertainties will be taken in the BioDME project, which is financed through the EU 7th Framework Programme and the Swedish Energy Agency (*resource mobilisation*). The Swedish Energy Agency granted SEK 100 million (€10 million), although this sum was deducted from the SEK 237.5 million (€24 million) that Chemrec was awarded already in 1997 (Rudberg, 2008). The total budget of the project is €28 million (Chemrec, 2008a)

Under the project, Chemrec and the Danish catalyst developer Haldor Tropsoe will design and build a DME plant located at the Smurfit Kappa mill in Piteå, integrated with the existing black liquor gasification pilot plant. With the new facility in operation, 4 tonnes of DME can be produced daily (*entrepreneurial experimentation*) (Chemrec, 2008a; Rudberg, 2008).

The project is coordinated by Volvo and set to demonstrate the complete infrastructure of BioDME production, distribution and application in a test fleet of 14 heavy-duty vehicles (*market formation*). Together with the component supplier Delphi, Volvo will develop an injection system for heavy-duty DME vehicles (Chemrec, 2008b). The participation of Delphi is seen pivotal for making the DME technology commercially interesting, since it will enable Volvo to acquire the injection system from a supplier and enable future series production of DME vehicles (Röj, 2009). In addition, the 14 DME vehicles will be fuelled and operated in field experiments at four locations in Sweden: Piteå, Göteborg, Stockholm and Jönköping. The project partner Preem will construct the filling stations, while Total will develop fuel and oil specifications (Chemrec, 2008b; Rudberg, 2008). The alliance underlying the DME project thus includes all the necessary industrial actors for demonstrating the complete infrastructure of DME.

If the project is realised by 2010, Chemrec will be the first system builder to have achieved continuous production of second-generation fuels.[247] It will, thereby, not only strengthen *market formation* but also be in a position to strengthen *legitimation* by illustrating the fact that DME is a realistic transportation fuel for the future (Rudberg, 2008).

However, even if the legitimacy of DME is strengthened, it will by no means be sufficiently strengthened to ensure future commercial success. DME is still a new type of transportation fuel and several incumbent firms still oppose its widespread use. For example, the automotive manufacturers Volkswagen and Daimler have clearly expressed opposition to the introduction of DME on the European market (Keppeler, 2007; Drescher, 2008), and even some of the oil companies participating in the BioDME project have expressed scepticism towards the introduction of DME as a new fuel in Europe (Eriksson, 2009; Hervouet, 2009).[248]

In addition to the BioDME project, a second step towards realising the potential of black liquor gasification has been taken. In 2009, the Swedish Energy Agency granted Chemrec and the biorefinery Domsjö Fabriker in Örnsköldsvik SEK 500 million (€50 million) for the first commercial-scale production facility of renewable transportation fuels from black liquor. The total investment cost is calculated at approximately SEK 3,000 million (€300 million), the plant has a planned capacity of 100,000 tonnes of DME (or 140,000 tonnes of methanol) per year, and the final decision on project procurement is planned for autumn 2011 (Landälv,

[247] Choren has a demonstration plant under commissioning that may come into operation before Chemrec.

[248] Preem is part of the DME project in Piteå but state that it is not a fuel it prefer, given that new infrastructure needs to be constructed (Eriksson 2009). According to Véronique Hervouet (2009) at Total, it does not believe in DME for mature markets such as in Europe or North America, but perhaps rather in Southeast Asia and China. Total's interest in the project is in learning about the technology; the company is involved in many different technology tracks concerning renewable fuels, with BioDME being just one. However, Total is one of the mineral oil companies that has announced an interest in investing in the semi-commercial plants that will constitute the next steps in Piteå and Escanaba (Rudberg 2008).

2010).[249] The grant is, however, contingent on approval by the EU Directorate General for Competition according to the state aid rules (Domsjö, 2009).

The second set of uncertainties that must be reduced to attract future investors is related to how the actors manage to reduce institutional and market uncertainties. This set of uncertainties is largely shared with the other projects for second-generation fuels and will be further discussed in Chapter XI.

[249] Co-production of DME and Methanol will be possible at any ratio between the two.

Box 7.2: Strengthening the network of actors in biomass gasification

With the creation of the BLG programme, a network of actors with an interest in black liquor gasification was significantly strengthened. To begin with, the research institute ETC in Piteå became the coordinator of the programme. Founded in 1989, it had long focused on experimenting with large-scale pilot equipment for combustion and gasification research. With the BLG programme, its resources increased significantly and it began to focus on the development of the Chemrec pilot plant, also located in Piteå. In addition to the research activities at ETC, research was also undertaken at Chalmers, Luleå and Umeå University, as well as at the research institutes STFI Packforsk (now Innventia) and the Corrosion Institute (Gebart, 2008).

With all the activities taking place at ETC and Chemrec, a wide network of firms interested in utilising biomass and black liquor for heat, electricity and renewable transportation fuels has emerged in and around Piteå. One of the first firms to become involved was the local ventilation and sanitation installations firm Infjärdens Värme AB (IVAB). It constructed the pilot plant for Chemrec when Babcock went bankrupt. Through its mechanical workshop, it has been engaged in constructing other laboratory equipment for gasification and combustion at ETC. Since 2008, it has been working with ETC to develop a new type of EF reactor for biomass powder (Gebart, 2008). The project is financed by the Swedish Energy Agency with SEK 16.8 million and involves both the development of a pilot-scale reactor and the adoption of a biomass powder technology in operation at the lime kiln at Kappa Kraftliner in Piteå (Energimyndigheten, 2009a).

The interest in gasification has inspired the company MEVA, in Skellefteå, to enter the TIS. Together with ETC, it is developing a new type of cyclone gasifier for small- and medium-scale district heating systems. They are currently constructing a small pilot (1MW) and has plans for a 10MW demonstration plant in the town/district of Hortlax, located close to the town of Piteå (Gebart, 2008). In 2008, a science park was inaugurated with a strong focus on developing and supporting companies working towards the future of "biorefinery" (Bergman, 2008).

The Department of Energy Technology and Thermal Process Chemistry (ETPC) at Umeå University have also started developing new ideas for enabling biomass gasification. They have been working with pre-treating biomass, thereby changing its physical properties through the process of torrefaction (see Chapter III). The technology is well aligned with standard coal gasification technologies, since it most likely can be used without having to adapt the reactor or any of the downstream processes (Nordin, 2008).

The technology is being developed by ETPC in collaboration with Övik Energy and the company Bio Energy Development North, which was started by researchers at ETPC. A pilot plant has been constructed and the Swedish Energy Agency is financing the construction of a commercial-sized demonstration plant in Örnsköldsvik. A research programme has also been set up to further support knowledge development and entrepreneurial experimentation based on the torrefaction of biomass. The total financing from the Swedish Energy Agency in this project is SEK 41 million (Energimyndigheten, 2009b).

7.3 The system builders' transformative capacity, system weaknesses and the potential role of policy

In this section, the four research questions specified in Chapter II will be revisited. Answers to each question will be provided for the case of Sweden by analysing the histories of fluidised bed and entrained flow gasification. The research questions were formulated as:

1) *Who act as system builders in the different national contexts?*
2) *What characterises the nature and extent of the system builders' transformative capacity?*
    a) *How do the system builders make use of the general structure in which they are embedded to form or strengthen the structure and the various functions of the TIS?*
    b) *To which extent do the system builders manage to strengthen the structure and functions of the TIS?*
3) *What are the limits to the system builders' transformative capacity and how can these be explained?*
4) *Given these limits, which system weaknesses remain to be resolved by system builders and policymakers on different levels (national and EU)?*

This section is divided into two parts. Research Questions I and II will be analysed in the first part. The discussion will depart from the structure during each episode and identify who have been acting as system builders, and describe the nature and extent of their transformative capacity. In the second section, the focus shifts towards analysing and explaining the limits of the system builders' transformative capacity, identifying the main system weaknesses and discussing the potential role of system builders and policymakers in addressing these weaknesses.

7.3.1 The nature and extent of the system builders' transformative capacity

By the end of the oil crisis in 1986, a technology and actor structure had been created in Sweden with the capacity to build atmospheric CFB gasifiers for oil substitution in lime kilns. The structure consisted of Fläkt Industri, Götaverken and a few such plants that were installed at paper mills in Sweden and abroad. Several suppliers and customers had gained experience with the technology. One of the most advanced pilot plants in the world for the pressurised gasification of peat and biomass had been constructed by the Department of Thermal Processes in Studsvik, which later became the firm TPS. In addition, the activities of Nynäshamn Petroleum had resulted in the creation of the consulting company Nykomb Synergetic, as well as the granting of a patent on black liquor gasification. The patent was subsequently acquired by Chemrec, which experimented with new methods for chemical recovery.

In this first episode, one can argue that Studsvik and Nynäshamn Petroleum were the system builders, since they acted to build new types of structures and strengthened the various functions. Due to the crises at the time, they were able to mobilise financial resources from the government, launch projects and create alliances (networks) for commercialising their technology options. Through their actions, they came to strengthen the functions of *knowledge development, entrepreneurial experimentation* and *materialisation* for EF gasification, atmospheric CFB and pressurised BFB gasification.

A commercial break through was, however, not possible with pressurised BFB and EF coal or black liquor gasification. Studsvik encountered technical challenges and was not awarded, along with Götaverken, the contract with Kemira. At least one such project would probably have been necessary to resolve the remaining technical issues, but no additional customers were to be found.

Nynäs Petroleum had obvious problems strengthening *legitimation,* since the use of coal (EF gasification) was seen as controversial and it had no real interest in pursuing black liquor gasification, even though the technical director at the company invented and patented the process. In addition, when Nynäs encountered the intentional resistance of Vattenfall and Stockholm Energy, the plans for a large-scale poly-generation plant had to be terminated, even though the government had already approved the project.

In the case of atmospheric CFB gasification, Götaverken was successful in developing the technology for substituting oil in lime kilns. This was an incremental type of innovation for Götaverken, since it could draw heavily on its development of CFB boilers. Götaverken was already one of the world leaders in boiler technology and had established networks within the pulp and paper industry (Koornneef et al., 2007). Compared to Studsvik and Nynäs

Petroleum, Götaverken did not need to build a new type of structure to succeed with atmospheric CFB gasification. As a result, the design space of lime kiln gasification appears to have co-developed within the design space of fluidised bed combustion.

The activities undertaken by Götaverken, and its customers, strengthened the technology and actor structure of the TIS, as well as the functions of *knowledge development, entrepreneurial experimentation, materialisation, market formation, legitimation,* and *direction of search* of the TIS. The activities undertaken did not, however, align the institutional structure to the technology. Hence, when the price of oil fell in 1986, interest in biomass gasification, oil substitution and alternative fuels fell along with it.

Soon after the oil crisis, the *direction of search* shifted to large-scale electricity production from domestic resources due to the Chernobyl accident and the increased controversy of nuclear power. Chemrec took over the role of system builder from Nynäshamn Petroleum, who was not interested in pursuing black liquor and biomass gasification. With the shift in *direction of search*, they could draw upon new resources in the structure and formed an alliance with Kvaerner, who by then had acquired Götaverken. The alliance was later strengthened through Nykomb Synergetics' entry into the TIS. The alliance, thus, had extensive experience with gasification from the first episode, and it managed to advance the technology by establishing a wide range of atmospheric and pressurised pilot plants, as well as a commercial-scale Booster plant in New Bern, USA. The Chemrec technology was also identified as strategically important to Sweden for reducing its dependency on nuclear power. It could, therefore, mobilise a large grant totalling SEK 237.5 million (€24 million) from the government for the construction of an initial semi-commercial demonstration BLG IGCC facility at AssiDomän's pulp and paper mill in Piteå. Although the large-scale BLG IGCC was never constructed, Chemrec and its allies managed to strengthen *knowledge development*, *entrepreneurial experimentation, materialisation, resource mobilisation,* and *market formation* of the TIS.

The new *direction of search* forced two new actors, Vattenfall and Sydkraft, to enter the TIS. However, due to Vattenfall's and Sydkraft's intentional resistance, Studsvik/TPS was unable to create an alliance with the two utilities and with Götaverken/Kvaerner to further develop biomass gasification for large-scale power production. In addition, Studsvik/TPS was unable to develop the smaller scale atmospheric BIGCC technology suitable for the numerous municipal-owned local utilities, since the government was unwilling to provide more than 50 percent financing in demonstration projects. In order to survive, TPS was forced into finding contracts abroad. Consequently, the activities undertaken by TPS strengthened the TIS of biomass gasification as a whole, but not the TIS in Sweden until it re-entered around 2000.

Instead, one could perhaps argue that Sydkraft and Vattenfall took over the system builder role in Sweden. However, in terms of their transformative capacity, they mostly strengthened *knowledge development*, *entrepreneurial experimentation* and *materialisation* in Finland. They thus came to strengthen the Finnish actor and technology structure, consisting of Tampella and its pilot plant, VTT and its science and technology infrastructure, and Foster Wheeler. Sydkraft strengthened, however, *materialisation* in Sweden with the completion of the Värnamo plant.

By the end of the 1990s, the BIGCC technology was successfully demonstrated in Värnamo but the plant was mothballed. At the time, the *direction of search* had changed−the electricity market was being deregulated and electricity prices were expected to fall. In addition, the decommissioning of nuclear power was no longer seen as a pressing issue for the utilities. As a result, Sydkraft and Vattenfall were no longer interested in pursuing the technology.

Vattenfall's and Sydkraft's motives for engaging in new technology development can, of course, be questioned. Were they really interested in developing alternatives to nuclear power, or were they only interested in delaying decommissioning for as long as possible? Regardless of the answer to that question, it is clear that whilst Vattenfall and Sydkraft strengthened the TIS of biomass gasification in Europe as a whole, they did not build on the Swedish structure developed in the previous episode.

As a result, by the end of the second episode the actor and technology structure for realising FB gasification in Sweden was not significantly stronger than it was in 1986, even though a successful demonstration had been completed in Värnamo. The situation for Chemrec, however, was quite different. It had considerably strengthened the actor and technology structure for BLG both in Sweden and abroad. However, by the end of the 1990s, the planned large-scale project was abandoned by Kvaerner and AssiDomän, and Kvaerner's shares in Chemrec were put out for sale.

The intentional and frictional resistance of Vattenfall, Sydkraft, and later Kvaerner and AssiDomän forced the considerably smaller companies of TPS and Chemrec to the brink of ruin. However, they managed to survive until the third episode, when the *direction of search* was once again strengthened in favour of alternative fuels. Under this new *direction of search*, new actors entered the TIS and the system builders could draw further resources from the structure.

To start with, Nykomb Synergetics and the Swedish Energy Agency saved Chemrec from bankruptcy. Jointly, the three actors assumed the role of system builder and began strengthening the structure and functions of the TIS by supporting Chemrec's technology development in collaboration with the unique competencies at the Oak Ridge National Laboratory for *a)* improving the refractory lining, and *b)* restarting the New Bern plant with the new lining. They acted to include BLG in the IEA agreements, supporting the remaining expertise within the field through a very difficult time. They also initiated the BGL Programme, through which more than 50 percent funding was made possible and which enabled them to *a)* construct the new pilot plant in Piteå, and *b)* create a research infrastructure for black liquor gasification at three universities and two specialised research institutes in Sweden. Through these actions, the system builders managed to strengthen *knowledge development, entrepreneurial experimentation*, *materialisation,* and *resource mobilisation* of the TIS in Sweden.

With the new actor and technology structure in place, Chemrec could attract a new set of owners and significantly improve the company's equity situation. In addition, they managed to mobilise further resources from the EU and set up a new alliance for demonstrating the entire value chain of black liquor gasification, including the complete infrastructure for using DME as a fuel for heavy-duty vehicles. If the project is completed as planned by 2010, Chemrec and its allies will have further strengthened *resource mobilisation*, *knowledge* *development, entrepreneurial experimentation*, *materialisation*, *market formation*, *legitimation* and *direction of search*.

As a result of the various activities undertaken to strengthen Chemrec, various spin-off and related activities have been created (see Box 7.2). Hence, the collective dimension of the innovation and diffusion process has also been strengthened (the *development of positive externalities*).

With regard to fluidised bed gasification, in 2000, there were several actors interested in commercialising FB gasification for the production of liquid fuels. Volvo had an interest in developing DME as an alternative fuel, the Swedish Energy Agency was seriously interested in “saving” Värnamo, and TPS was provided an opportunity to re-enter the TIS in Sweden.

There was, later, also a call for proposals from the European Union within the context of the 6th Framework Programme for the demonstration of second-generation fuels. A network of actors around the Värnamo facility therefore emerged and attempted to undertake system building activities. Although the actors had many and perhaps conflicting goals, they all acted with a common interest of redesigning the Värnamo plant as a research facility for the demonstration of clean hydrogen-rich synthesis gas. Consequently, the research project CHRISGAS was set up and the network was, thereby, extended to include a wide range of EU-based partners.

The Swedish Energy Agency played a key role in the Swedish-based network for mobilising resources and establishing an actor structure. This new structure included the creation of a new actor owned by Växjö University (VVBGC) which would own the plant, as well as apply for further resources and coordinate its research activities. The intention was that this improved structure would strengthen *knowledge development, entrepreneurial experimentation,* and the *materialisation* of a new science and technology infrastructure that would be valuable to all of Europe and hopefully, over the long-term, contribute to *market formation*.

However, the above-mentioned functions were not strengthened and the vision could not be realised. VVBGC and Växjö University had been responsible for finding additional financing for the CHRISGAS project and an additional project, WASTE, was supposed to start up the Värnamo facility and thereby share some of the associated costs. These plans failed and as a result the funding required for reconstructing the Värnamo facility increased. Hence, when VVBGC applied for SEK 250 million (€25 million) instead of the expected SEK 182 million (€18 million), the Swedish Energy Agency responded by requiring industrial ownership of the plant through a new company (Company A). Industry would thereby co-finance reconstruction and initial demonstration with at least SEK 68 million. In return, it was offered ownership of the technology that was developed, as well as the responsibility for commercialising the technology. To date, this company has not been created and the Värnamo plant has once again been mothballed.

In the third episode, in parallel with the development of Värnamo and perhaps due to all of its problems, a new potential system builder has emerged in the form of Göteborg Energy. It has managed to create an alliance of firms and establish research activities at Chalmers that might lead to the first semi-commercial-scale demonstration plant for BioSNG production based on the FICFB gasification process developed in Austria. Through its efforts, it has strengthened the actor structure by attracting E.ON and Metso Power, as well as broadened Chalmers' work in the field. It has also strengthened the technology structure through financing the construction of a pilot facility at Chalmers. Through this, it has strengthened the functions of *knowledge development, entrepreneurial experimentation* and *materialisation*.

After having described the three episodes of fluidised bed and black liquor gasification, it is now possible to provide short answers to RQ1 and RQ2. With respect to RQ1 and black liquor gasification. Chemrec has been the primary system builder but Nykomb Synergetic and the Swedish Energy Agency have also undertaken system building activities that have been crucial to the survival of Chemrec and the development of the knowledge field. In the field of fluidised bed gasification, no single system builder was identified but rather a wider network of actors. This national network was strong during the 1980s, but weakened during the 1990s when the two major utilities, Sydkraft and Vattenfall, chose to strengthen the actor and technology structure in Finland instead of that in Sweden. Since 2000, the Swedish

Energy Agency, TPS, VVBGC (but also others) have attempted to take on the system building role, thereby strengthening the Swedish actor and technology structure, but instead it has continued to deteriorate. More recently, Göteborg Energy has taken on the role of a system builder and may enable the first semi-commercial-scale demonstration plant for BioSNG production based on the FICFB gasification process developed in Austria.

As the system builders have emerged from different contexts, the nature and extent of their transformative capacity (RQ2) has been quite different from one another. In black liquor gasification, Chemrec has been able to utilise the existing technology structure by drawing upon fossil gasification and technology developed in Nynäshamn for producing methanol and the ceramic technology developed for space shuttles. Chemrec has also managed to attract actors to the field by aligning the technology to the interests of a) the pulp and paper industry for boosting capacity in existing recovery boilers and finding additional revenues, and b) Volvo’s and other actors’ interest in DME. In addition, resources have been possible to mobilise due to the nuclear crisis in the 1980s and the current climate crisis.

As a result, Chemrec has been able to strengthen all eight functions, *resource mobilisation, knowledge development, entrepreneurial experimentation, materialisation, legitimation, direction of search, development of positive externalities,* and *market formation* for less advanced applications. It has also built and strengthened the structure of the TIS. Chemrec has, for example, been able to build pilot, demonstration and commercial-scale plants for less advanced applications (technology), attract actors (actors), create national and international knowledge networks, as well as form alliances with incumbents (networks).

The network of system builders in fluidised bed gasification has been able to draw upon existing actors and technologies in fluidised bed combustion. Götaverken explored atmospheric gasification and managed to sell a few commercial-scale lime kiln gasifiers, while Studsvik pressurised the technology and made attempts to develop it for the production of methanol. Studsvik also developed a less advanced atmospheric lime kiln gasifier, but came too late into the market. Hence, when an interest in electricity production from biomass gasification emerged, Studsvik/TPS had two technology options.

The atmospheric option was aligned with the interest of the municipal companies, as the technology was promising for developing BIGCC on a smaller scale that was suitable for the existing district heating networks in Sweden. Several municipal companies invested in TPS and efforts were made to develop the technology. However, there were no government funding available that could cover more than 50 percent of the investment costs, and the municipal companies were not willing to take the added risk. Similar projects were instead pursued by TPS with international partners.

The second option was the pressurised technology. It could have been further developed for large-scale BIGCC, which was in line with the main interests of Vattenfall and Sydkraft. However, these major utilities did not choose to build on the experience from the previous episode in Sweden, and made alliances with Finnish firms instead.

In the third episode, most of the actors with competence in building fluidised gasifiers had exited the TIS. However, a small network of actors re-emerged and they could draw upon Volvo's interest in DME, the Swedish Energy Agency's interest to save the Värnamo facility, and the municipal of Växjö to become a fossil free community.

New structures were created, such as the knowledge network (CHRISGAS), and a new organisation (VVBGC), and substantial resources could be mobilised from the EU. With these resources, *knowledge development* and *entrepreneurial experimentation* could be strengthened. However, they were not sufficient to re-design and take the Värnamo facility into operation and the network failed to create an actor structure, with strong Swedish national interest, that could appropriate on the future knowledge development at such a facility.

7.3.2 Limits to the system builders' transformative capacity, system weaknesses and the potential role of policy

The final part of the discussion will begin by analysing the limits of the system builders' transformative capacity and identifying the main system weaknesses. This will be followed by a discussion on the role of the system builders and policymakers in addressing these weaknesses.

Explaining the limits to the system builders' transformative capacity and identifying the main system weaknesses

The network of actors in fluidised bed gasification, including Götaverken and Studsvik/TPS, was able to strengthen the TIS in Sweden during the first episode. However, due to the intentional resistance of Vattenfall and Sydkraft, their ability to act as a system builder was very limited during the second episode. Nevertheless, in the third episode a new network of actors with an interest in fluidised bed gasification could be created, consisting primarily of TPS, VVBGC and the Swedish Energy Agency but also many more actors. With time, the Swedish Energy Agency identified the need for creating additional structure, in terms of a new company called Company A. The purpose of Company A was to appropriate on the knowledge development at Värnamo and, thereby, be responsible for commercialising the technology and co-financing the reconstruction of the plant. The alliance managed to mobilise resources from the EU but the system builders were unable to strengthen the functions (except *resource mobilisation* and, to a limited degree, *knowledge development*) or find investors for Company A, due to various limits to the system builders' transformative capacity.

The explanation for these limits can be found in the second episode, where the actions of Sydkraft (and Vattenfall) had primarily strengthened the TIS in Finland. Thus, the IPR of the Värnamo facility did not belong to any of the Swedish actors, but to Foster Wheeler. It had constructed the plant in the first place and only granted the Swedish actors a limited IPR agreement. By then, Foster Wheeler had also become involved in similar projects, but in an alliance with VTT and Stora Enso (see Chapter VIII). Its interest in supporting a potential alliance of competitors in Sweden must therefore be seen as limited. While the Värnamo plant may be located in Sweden, for the time being it should be seen as an "outpost" of Foster Wheeler rather than a "golden egg" for any Swedish-based alliance.

Even if the IPR problem could be resolved, it would still be difficult to create Company A due to the weak actor structure. There is a lack of Swedish companies[250], with a strong

[250] Based on this study, it has not been possible to identify any other actors in Sweden that could leverage the investment in Värnamo, except certain customers who could build one or two such plants for themselves.

competence in the field, which could appropriate on the knowledge development at Värnamo by building subsequent plants.[251]

With regard to the trajectory of entrained flow gasification of black liquor, Chemrec managed to survive due to the actions undertaken by the Swedish Energy Agency and Nykomb Synergetic. Together, they managed to strengthen the actor and technology structure of black liquor gasification and all the functions, except for *market formation*. However, even though Chemrec appears to be doing well today, the weak actor structure in Sweden (in terms of the lack of a capital goods industry) is still a factor it has been forced to work around. Since Chemrec is a small company, it must rely on strong alliances with incumbent actors to succeed. By itself, Chemrec are unable to take on large projects and secure the necessary financial guarantees for turning chemical pulp mills into biorefineries that produce renewable transportation fuels.

Although Chemrec has managed to create strong alliances with international actors, other small-scale actors entering the TIS will have to operate in a structure lacking large capital goods suppliers that can enter alliances and provide complementary competencies and resources. Hence,

The first system weakness is the lack of capital goods industries with the capacity of entering into alliances, appropriating on knowledge development, and constructing large-scale plants.

The joint transformative capacity of Chemrec, Nykomb Synergetics and the Swedish Energy Agency appears, however, to be sufficient for compensating for this system weakness by developing alliances with various international actors. Through such an alliance, Chemrec may still play an important role in the construction of full-scale plants for converting black liquor into transportation fuels and other chemicals. Nevertheless, small firms or single individuals that are not part of a strong structure cannot be expected to establish alliances with multinational corporations.

[251] The only company with any real competence in FB gasification at the time was TPS. Götaverken had long since exited the TIS and was owned by Metso Power. They could possibly have been a good partner for TPS or taken over TPS's role when they went into reconstruction and later exited the TIS. However, the IPR agreement with Foster Wheeler explicitly denied the actors the chance to enter such an alliance with Metso, and it is highly unlikely that Foster Wheeler would help their principal competitor gain such an advantage.

A second system weakness relates to the formation of markets. The actors have worked to create niche markets for the technology by occupying less advanced applications, such as lime kilns or the Booster, with which the actors have been able to gain commercial experience and continue the development of the technology for more advanced applications. Less advanced applications have though been fewer in Sweden and the actors have, thus, had limited possibilities to learn from them.

As importantly, the system builders have not acted, or been able, to influence market formation for advanced applications through aligning the institutional framework to the technology. This may be explained by the fact that the system builders have always been relatively small actors and highly dependent on the creation of alliances with very large actors.[252] It has not been in the interest of the large actors to influence the institutional framework in order to form markets for emerging technologies such as biomass gasification. First, the utilities have limited interest in supporting emerging technologies with the potential to replace even parts of their nuclear capacity. Second, the pulp and paper industry has limited interest in promoting new technologies that would increase competition for and/or the price of biomass and electricity. Any special provisions for emerging biomass-based technologies and other incentives that would increase the price of biomass and electricity would, therefore, not be favoured by industry and have not been encouraged.

In addition, the dominant belief among policymakers, at least prior to the 1990s, appears to have been that research and development, in combination with some additional investment support, would be sufficient for bringing down the price of emerging technologies to the level of conventional technologies. The new technology would then eventually replace conventional technology, which in this case was nuclear power. Hence, through the history of biomass gasification in Sweden, there is an absence of efforts to form markets by institutional change.

[252] There is a possible exception in TPS, as it was backed by a wide range of municipal utility companies. Together they tried to develop the atmospheric BIGC technology, which was well aligned with the government's interest in increasing electricity production form biomass at the time, the interests of the municipal companies and the existence and size of district heating systems in Sweden. However, the municipal companies refrained from investing in a first demonstration plant since they could not get above 50 percent funding from the government.

Given the introduction of the green certificates in Sweden in 2003, however, this linear perspective on the innovation process may be understood to shift to a somewhat less linear one. Under the new system, special provisions were granted for emerging and renewable technology, but only for those that currently have the lowest cost and not necessarily those with the highest potential over the long-term. Hence, the potential of the system to actually drive down the cost of radically new and, at the beginning, costly technologies such as BIGCC must be seen as extremely limited without additional support (Bergek and Jacobsson, 2010). With this type of instrument, biomass gasification will not be developed since it is initially more expensive to produce, even though it is more socially desirable than first-generation fuels. Hence,

The second system weakness is the lack of an institutional framework that recognises the need for creating specific market preconditions in support of emerging technologies.

The two weaknesses are general, even though Chemrec has been capable of manoeuvring past the first due to actions undertaken by the Swedish Energy Agency. However, there are also weaknesses that are specific for the two trajectories.

With regard to Chemrec, it has been able to create alliances with all major actors involved in demonstrating the production of DME from black liquor, for distribution and for using it in 14 new DME heavy-duty vehicles. The series production of future DME vehicles appears to have been solved with Delphi's participation in the development project and with securing the supply of necessary components for the series production of DME vehicles.

If the current BioDME projects and the first pre-commercial-scale demonstration facility at Domsjö are successful, the alliance will have considerably strengthened the legitimacy (*legitimation*) and *direction of search* for DME as a new alternative fuel. In addition, if successful, the system builders will have created a limited market with dedicated fleets utilising their own fuel infrastructure[253] in cities and towns (primarily in Sweden), thereby strengthening *market formation*. However, this may not be sufficient for a larger market to

[253] Such a market can, for example, consist of city buses, garbage collection vehicles, logging trucks, etc., which return to the same location every night and have a limited need for many fuel stations over great distances.

materialise since there is no infrastructure developed for distributing DME anywhere in Europe. Hence,

The third structural system weakness is the lack of a technology infrastructure for diffusing DME as a transportation fuel in Europe.

The development of such an infrastructure is questioned by Volvo's main competitors (such as Volkswagen and Daimler) and by the oil industry (such as Preem and Total). The system builders have, thus, been limited in its capacity to strengthen *direction of search* and *legitimation* for the use of DME in the EU. Overcoming the intentional and frictional resistance of the incumbents will, of course, take time and require considerable resources compared to if the incumbents were in favour of such a development.

Dedicated fleets with their own fuel infrastructure is also the type of market that has been targeted by advocates of BioSNG (methane) as a transportation fuel such as Göteborg Energy. The system builder in focus has managed to set up an alliance with firms consisting of E.ON, Metso Power, Repotec and a catalyst developer for demonstrating the technology on the scale of $20MW_{th}$. However, it has still been limited in its capacity to strengthen *legitimation* and the *direction of search* for using methane as a transportation fuel. The primary explanation for this is that methane is not a diesel fuel and Göteborg Energy has, so far, been unable to create an alliance with manufacturers of heavy-duty vehicles for further engine development. The heavy–duty vehicles using methane therefore suffer from lower energy efficiency and engine robustness compared to those operating on diesel. Hence:

The fourth system weakness is an incomplete technology and actor structure for using BioSNG as a transportation fuel in heavy-duty vehicles.

Nevertheless, Volvo demonstrated the use of methane in a diesel engine in a line-up of various fuel alternatives in 2007. If further developed, methane could be a good alternative or complement to DME. Steps in that direction have more recently also been taken (Hedenstedt, 2010). The success of such a development is too early to foresee, and the current interest from other manufacturers of heavy-duty vehicles is extremely limited. The alternative for Göteborg Energy is, of course, to continue promoting BioSNG for personal vehicles, although the physical infrastructure to support this is still under-developed in most of Europe.

Role of system builders and policymakers

The role of policymakers is to address those of the above-mentioned system weaknesses that are currently beyond the transformative capacity of the system builders. Out of the four system weaknesses, the first two require a longer discussion on how they can be addressed. The discussion on the first system weakness will be presented in this section. The second system weakness is addressed in Chapter XI.

The role of policy with respect to the third and fourth system weaknesses is seen as relatively uncomplicated. Policy can, of course, focus on supporting the creation of infrastructure for BioSNG and DME, as well as supporting engine development for the use of methane in diesel engines. In addition, the system builders have proven to have great capacity for creating various types of alliances, and with time will probably be able to overcome these system weaknesses through working in established networks with policymakers and other actors.

With respect to the first system weakness, no policy can be expected to turn the clock back to the 1980s and reconstruct the previous industry and technology structure. Instead, the example of Chemrec illustrates that through active and "technology-specific" policymaking, it is possible to strengthen a weak TIS structure and, thereby, the transformative capacity of the individual actors. A stronger structure enables individuals and small firms to draw resources from the structure to create or engage in the necessary national and international alliances.

With the recent success of Chemrec, *direction of search* has been strengthened and a wide range of new actors and technologies has emerged. As a result, the design space of biomass gasification has been extended; networks and other structural elements as well as various functions of the TIS, such as the *development of positive externalities*, have been strengthened. Hence, even if none of the new Swedish actors, including Chemrec, can take on entire multi-billion Euro projects to build new biorefineries by themselves, they may still fulfil very important niches and do so in a wide range of knowledge areas.

Based on the Swedish experience, strong lessons for policy can be drawn. In technology development projects of this type, the risk of failure is great. However, as is clear from the history of black liquor gasification, failure is a part of a long learning process. Before financing such projects, therefore, it is necessary to identify:

a) what type of science and technology infrastructure is created. Is it useful beyond a single experiment or demonstration and, if so, who can continue to learn from it?

b) who has the ability to appropriate the benefits of the knowledge development, even if the project itself fails?

Rather than only focusing on succeeding with the individual project, which of course remains important, it is also necessary to identify which actors can learn from an eventual failure. In the case of Chemrec, if it fails to demonstrate the production of renewable fuels and other chemicals, it will still have benefited from the experience of trying. Chemrec will have all the proprietary rights to the technology, and the investments in the pilot plant can be used for experimenting with other applications or finding new uses for the knowledge already developed. The science and technology infrastructure that has already been constructed can continue to be used for research.

If tax payers in Sweden finance technology development through, for example, the Swedish Energy Agency or through utilities owned by municipalities or the government, this should only be done when an actor and technology structure exists (or is created) that can appropriate the benefits of knowledge development beyond a single experiment (successful or not). Hence, policymakers who would like to address the main system weakness in Sweden should neither accept the fact that the main science and technology infrastructure is created or strengthened in a different country, nor that the principal actor with the ability to appropriate the benefits of knowledge development moves back to Finland (or somewhere else) once the project is over.

7.4 Conclusions

In fluidised bed gasification, a network of actors has attempted to undertake system building activities since the 1970s. In the first episode, the network was strong and consisted of prominent actors such as Götaverken, ABB Fläkt and Studsvik/TPS. However, when Sydkraft and Vattenfall entered the TIS in the 1990s, the main actors from the previous episode exited and the network was weakened. In the beginning of 2000, TPS could return and a new, but also weak, network of actors could be formed—primarily consisting of TPS, the Swedish Energy Agency, VVBGC but also others. In black liquor gasification, the main system builder has all along been Chemrec, but pivotal system building activities were also undertaken by Nykomb Synergetics and the Swedish Energy Agency. In particular, the actions undertaken by the Swedish Energy Agency in enabling the survival of Chemrec was highlighted. Similar actions were attempted to support a new network of actors in fluidised bed gasification and save the Värnamo plant, but so far these have failed and the only remaining actor from the first episode, TPS, is bankrupt. More recently, Göteborg Energy has taken on a system building role and attempts are undertaken to further develop and commercialise the FICFB technology, originally developed in Austria (Chapter V).

As a technological field, biomass and black liquor gasification has been identified as strategically important for Sweden for the production of alternatives fuels, as well as large-scale renewable electricity with a capacity to contribute to the decommissioning of nuclear power in Sweden. As such, the system builders have been able to mobilise various resources from the government. However, the main actors, TPS and Chemrec, are quite small and rely on alliances with incumbent actors to succeed.

This is also where the histories of the both companies start to differ. Chemrec was able to create alliances (albeit fragile ones) with large incumbent actors in Sweden for developing the technology during the 1980s and 1990s. The alliances made it possible to strengthen the technology and actor structure of black liquor gasification. Although the project eventually failed and the alliance was dissolved by the end of the 1990s, a new alliance with Nykomb and the Swedish Energy Agency was established. The new alliance managed to create and strengthen a new actor and technology structure through which Chemrec could act. As a result, Chemrec’s transformative capacity was significantly improved and the new alliance has been able to strengthen all the functions of the TIS. Lately, a strengthened system has resulted in new entrants which have started experimenting with biomass gasification (Box 7.2).

In terms of TPS (and Götaverken), they could not overcome the intentional resistance of Vattenfall and Sydkraft. The two utilities did not act as system builders and they were not interested in building on the achievements made during the first episode. In addition, a market for TPS's smaller scale and atmospheric BIGCC technology could not materialise due to the lack of financial support from the government. As a result, TPS was forced to create alliances and find projects beyond Sweden's borders.

The alliances formed by Sydkraft and Vattenfall mostly strengthened the TIS of biomass gasification structure abroad (in Finland). As a result, the actor and technology structure in Sweden for fluidised bed gasification was weakened and the control over the Värnamo plant was "given" to Foster Wheeler. When attempts were made during the 2000s to revive the Värnamo plant for the creation of a new actor and technology structure that could appropriate on the planned technology development, they failed. Hence:

1. *The first system weakness is the lack of capital goods industries with the capacity of entering into alliances, appropriating on knowledge development, and constructing large-scale plants.*

Overcoming this weakness is beyond the capacity of individual system builders. Instead, policy has to focus on strengthening the structure. Policy intervention needs to focus on identifying and creating structures that are able to learn from failure and not just provide the best possibilities for securing the success of individual projects. Such a structure should, thus, consist of a science and technology infrastructure that is useful beyond a single demonstration and actors that are able to appropriate on the knowledge that is developed.

In addition to the above-mentioned structural weakness, three other weaknesses were identified:

2. *The second system weakness is the lack of an institutional framework that recognises the need for creating specific market preconditions in support of emerging technologies.*

The system builders have been limited in their capacity and may not even have attempted to create markets that go beyond natural niche markets such as those for oil substitution in lime kilns. The availability of such markets would have been of critical importance for the development of more advanced applications. Nor has policy opened up such markets by institutional change. Technology development based on a linear model has been manifested by a system that stimulates the diffusion of renewable technologies that currently have the lowest cost. The consequence of using such a system and the role of policy for addressing this system weakness will be further analysed in Chapter XI.

The system weaknesses mentioned above affect all trajectories, while the remaining two weaknesses concern only DME and BioSNG production.

3. *The third structural system weakness is the lack of a technology infrastructure for diffusing DME as a transportation fuel in Europe.*

Chemrec had been successful in creating various alliances for demonstrating the complete value chain of DME production, distribution and use in heavy-duty vehicles. To date, however, the major automotive manufacturers in Germany, such as Volkswagen and Daimler, as well as some of the mineral oil companies included in the alliance, are opposed to the widespread use of DME in Europe. It is expected that Chemrec will be able to address this weakness, mostly by targeting dedicated fleets with their own fuel infrastructure, but that policy would also have a role in supporting the development of a wider infrastructure.

4. *The fourth structural system weakness in Sweden is an incomplete technology and actor structure for using BioSNG as a transportation fuel in heavy-duty vehicles.*

The final system weakness concerns the use of BioSNG, where the system builder, until most recently, has been limited in his capacity to create alliances for demonstrating the use of methane in heavy-duty vehicles with the same high level of engine robustness and energy efficiency provided by diesel engines. The role of policy should be geared towards supporting such engine development and improving the fuel infrastructure for the use of BioSNG in personal vehicles.

Finland

Chapter VIII
Finland

The recent history of biomass gasification in Finland began in the early-1970s and has been, at times, closely intertwined with its development in Sweden, which has created some similarities between the two countries. However, the focus of development in Finland has primarily been on fluidised bed gasification for combined heat and power generation. Interest in alternative fuels did not pick up until 2003.

Just as with Sweden, the development of biomass gasification can be divided into three main episodes. For each episode a specific *direction of search* was dominant, influencing the evolution of the structure.

The first episode began during the 1973 oil crisis with the first serious experiments with biomass gasification since the Second World War. The *direction of search* at that time was influenced by the need to find a substitute for oil. Gasification technology was developed for lime kilns in the pulp and paper industry, but experiments were also conducted for electricity generation and the first plans for a large-scale pressurised peat gasifier were put in place by the chemical company Kemira for ammonia production. However, these plans were not realised until the beginning of the second episode.

The second episode began in 1986, when the *direction of search* quickly shifted towards large-scale production of electricity due to a sudden drop in the price of oil, the Chernobyl accident and the emerging climate debate. Interest in pressurised gasification picked up and the first *entrepreneurial experiments* were conducted with ammonia production and with electricity production based on the BIGCC technology. Two large experiments were performed by Finnish actors on behalf of Swedish customers. Several *entrepreneurial experiments* with less advanced applications for electricity production were also conducted during the episode. However, no real commercial break-through was made, and interest in electricity generation based on biomass gasification tapered off during the end of the 1990s.

A third episode began in 2003, when the *direction of search* shifted towards large-scale production of renewable fuels based on biomass gasification as a result of EU Directive 2003/30/EC, which created a vision of a substantial market within the EU. Based on previous experience, the Finnish actors were in a good position to further develop the technology. In parallel with the development of alternative fuels and as a result of increasing electricity prices, interest in combined heat and power production based on low value waste streams has picked up once again.

This chapter is divided into six main sections. The three main episodes will be outlined in the first three sections. These sections will focus on describing the interactions between actors and the characteristics of the emerging technological innovation system (TIS). The focus is on how the system builders act to create the emerging structure of the TIS by building the structure directly, but also by strengthening the various functions specified in Chapter II. Also included in the sections is a description of what the system builders consider to be necessary for realising their technology options on a commercial-scale. The fourth section provides a summary of the three episodes.

The fifth section of this chapter provides answers to the research questions (as specified in Chapter II). The discussion will start by identifying who have been acting as system builders, and describe the nature and extent of their transformative capacities. The focus then shifts to analysing and explaining the limits of the system builders' transformative capacities, identifying main system weaknesses, and discussing the potential role of system builders and policymakers in addressing these weaknesses. The sixth section of this chapter presents the main conclusions.

8.1 Episode I: 1970—1986. Oil and nuclear crises, and the first experiments with biomass and peat gasification

By the middle of the 20th century, 75 percent of primary energy demand in Finland was met by domestic sources such as hydroelectric power, wood fuel and peat (OECD, 1970). At the outset, Finland's dependency on imports of foreign energy sources such as oil and coal was relatively low. This gradually increased over time and coal became the country's preferred fuel.[254] Oil was not introduced on a large-scale until the late 1960s, when demand for electricity increased rapidly. In the relatively short period between 1960 and 1970, Finland's oil dependency increased from 20 to 50 percent (OECD, 1970). The government's energy policy strategy, presented at the OECD in 1970, predicted that electricity consumption would continue to grow rapidly during the 1970s and that future demand would best be met through imported oil until 1975, when the first nuclear reactors would come online. According to calculations by the state utility Imatran Voima, a total of 10 reactors with a capacity of 8,000MW was deemed to be necessary for meeting expected demand by 1990 (OECD, 1970; Kommonen and Rundt, 1976).[255]

The government's strategy was to increase Finland's dependence on oil until nuclear power came online. In retrospect, this can of course be judged as an unfortunate choice which, clearly, had to be revised in the wake of the 1973 and 1978 oil crises. Indeed, a wider set of fuels had to be introduced and used on a larger scale. For example, natural gas was introduced in 1975 and the use of peat, coal and biomass increased along with the rising price of oil and the introduction of investment support (Ericsson et al., 2004). The first two Soviet-built nuclear reactors did not come online until 1977 and 1980, respectively, due to delays during their construction (Kaikkonen, 2010). The Swedish company ASEA completed two additional reactors in 1980.

The original energy strategy had to be revised again during the latter part of the 1970s. During the construction of the first nuclear power plants, opposition against nuclear technology increased and the plan to further expand the programme to a total of 10 nuclear plants was heavily criticised (Kommonen and Rundt, 1976). In addition, an unforeseen slowdown in the world economy during the latter part of the 1970s made it possible to postpone further decisions on the planned fifth and sixth nuclear reactors until the mid-1980s (MTI, 1979, 1983).

[254] Finland had suffered from being isolated from sea transportation during winters. Coal, thus, became a preferable fuel since it is cheaper to store over long periods of time. Coal has continued to play an important role in the Finnish energy mix until the present day.

[255] The calculations were based on the rapid increase in the use of electricity during the 1960s, and expectations of even stronger economic growth in the future.

However, it is unlikely that these were the only reasons for revising the plans for further nuclear expansion. Sweden, for example, had similar plans but moved on and constructed a total of 12 reactors (Kaijser, 1992; Kåberger, 2002).

Finland made a different choice. During the oil crises, it had emphasised the strategic importance for the nation to further develop and make competitive their vast domestic peat and wood residue resources for energy production (MTI, 1979). Forest residues are abundant in supply from the domestic wood processing industry and Finland's peat resources are among the largest in the world (Statistics Finland, 2009).[256]

Finland also decided to favour combined heat and power (CHP) production over condense power production, and to use the heat load in the district heating systems (DH) for CHP as much as possible. To support its development, the government decided to substantially increase spending on energy research.[257] The priority within the field of energy research was made clear from the outset: the funding should be used to improve methods for harvesting peat and the collection of forest residues not used in the pulp and paper industry, and reduce the overall costs of using domestic resources (MTI, 1979). Such methods were also developed and local markets for peat could be created and used in CHP production (Asplund, 2009).

The government considered nuclear research too expensive and decided that it should not be given a priority in the research and development budget (MTI, 1979). Even though Finland's domestic industry was clearly pro-nuclear, the decision made sense—Finland never had a national capital goods industry for nuclear power and has never attempted to develop one. On the other hand, Finnish industry could benefit from increased efforts to develop domestic resources and the construction of CHP plants.

The focus of research and development efforts was the national capital goods industry, which had developed alongside the dominant pulp and paper industry (Lehtinen et al., 2004;

[256] Finland's peat resources have been estimated to be about 12,800TWh, which can be compared to total energy consumption in 2007 of 408TWH

[257] It was about one-fifth that of the other Nordic countries on a per capita basis until the late-1970s (MTI, 1979).

Donner-Amnell, 2009).[258] Its development had been supported over a long period of time, since the capital goods sector was part of a national strategy to increase the competitiveness of the pulp and paper industry. The essence of the strategy was to replace imported machinery with innovative domestic technology and thereby improve its competitive advantage on the world market (Donner-Amnell, 2000).

New, innovative pulp and paper technologies were developed by the machinery industry and pulp and paper companies in joint projects. The domestic pulp and paper industry also served as the first customers for the new technologies. Having a domestic customer, in combination with research and development support from the government, was seen as key for developing the most advanced paper technologies (Anonymous 1, 2009).[259]

In addition, co-existence and competition between various national manufacturers within the capital goods industry was stimulated by the pulp and paper industry to keep up the pace of innovation and generate price competition. During the 1970s and 1980s, the strategy eventually resulted in the existence of three dominant manufacturers—Tampella, Ahlström and Valmet—as well as various smaller and specialised suppliers. The two dominant corporations, Tampella and Ahlström, supplied not only paper machines but also energy and boiler technologies for electricity generation suitable for the domestic resource base (Anonymous 1, 2009).

When the oil crisis emerged, these manufacturers initiated the development of alternative combustion technologies. Some of these projects were also supported by various universities and the research institute VTT, in Finland. The goal of this development was to enable the combustion of more difficult, wet and heterogeneous biomass- and peat-based fuels, primarily for CHP production. As a result, experiments with variants of the fluidised bed combustion technology were initiated (Koornneef et al., 2007).

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258 The pulp and paper industry is very energy intensive and dependent on cheap raw materials and electricity. They consume about one-third of the electricity produced in Finland. It is also a sector that has come to dominate economic life in Finland—about one-quarter of export revenues is generated from the forest industry (even though it decreased to less than 20 percent in 2008) and it strongly influences all political arenas (Donner-Amnell, 2000, 2009; Statistics Finland, 2009; Uljas, 2009).

259 The common development of the industries appears to be by analogy with the common development of the capital goods suppliers, utilities and the Swedish government that Fridlund (1999) writes about.

Most of the technology development in this field took place in the Nordic countries, even though the Winkler fluidised bed gasification system had been invented in the US in 1922 and its first industrial installation was led by Foster Wheeler, also in the US, in 1979 (Koornneef et al., 2007). The pulp and paper industries in the Nordic countries provided a demanding home market, due to its insistence on using difficult by-products of the pulp and paper process as fuels (wood waste and sludge). However, other low grade fuels such as peat were also of particular importance in Finland. Even though the development work on fluidised bed technology took place in many countries, the specific demands and the size of the home market made the Finnish and Swedish capital goods suppliers among the front runners in the field early on (Koornneef et al., 2007; Thunman, 2009).

These capital goods suppliers were, thus, active in technology development with the purpose of reducing oil dependency, through technology substitution or by introducing various measures to improve the energy efficiency in the pulp and paper industry (Kivimaa, 2008). Since fluidised bed combustion and gasification are similar processes, they also started experimenting with biomass gasification as a means for replacing the fuel oil in the lime kilns with the biomass-derived gas from fluidised bed gasification.

8.1.1 Early entrepreneurial experiments in biomass and peat gasification

The research and development work on gasification was dominated by the incumbent capital goods industry, in particular Ahlström, and it was spun-off as an interesting application based on its development of fluidised bed boilers.

Ahlström started to develop the technology at Hans Ahlström Laboratory by building a $2MW_{th}$ pilot plant, intended for substituting fuel oil in the lime kilns (without any advanced gas cleaning). Due to the oil crises and a strong demand from the pulp and paper industry, a commercial market existed and gasification thereby found a first commercial application (*market formation*) (Anonymous 2, 2010).

Ahlströms first commercial installation had a maximum capacity of 35MW fuel power and came into operation in 1983 at Wisaforest Oy in Pietarsaari, Finland (Kurkela, 1989). Four plants were installed in total. Two of them were installed at mills in Sweden (Norrsundets

Bruks and ASSI in Karlsborg) and one at the Portucel mill in Rodao, Portugal (Kurkela, 2002; Palonen et al., 2006; Anonymous 2, 2010).

In 1983, Ahlström also initiated the development of the atmospheric CFB gasification technology for CHP generation together with Wärtsilä Oy. The plan was to clean the gas and use it in stationary diesel power stations based on Wärtsilä's Pielstick diesel engine. The technology was demonstrated at the scale of $3MW_{th}$, at the Ahlström laboratory and it was intended for installations in the range of 2.3-28MW of electricity and 2.9-35MW of heat (Kurkela, 1989; Anonymous 2, 2010). The project was terminated when Wärtsilä declared that it was no longer interested in pursuing it (Asplund, 2009; Anonymous 2, 2010).

The Technical Research Centre of Finland (VTT) supported the development at Ahsltröm with various type of gas analysis, etc., but had a minor role in the technology development at the time (Isaksson, 2009; Anonymous 2, 2010). VTT also made conceptual studies on pressurised systems. However, since it was believed that future electricity demand would be covered by nuclear power, the high development costs associated with the pressurised technology on a large-scale were discouraging (Leppämäki et al., 1976; Asplund, 2009).[260]

VTT also initiated additional *entrepreneurial experiments* and started experimenting with a simple up-draft gasifier from Volvo, which had been used during the Second World War. There were some experienced personnel at VTT that had been working with the technology during the 1940s, and they felt that it still had potential to be developed further and made several attempts to co-produce heat and electricity using a stationary diesel engine (*knowledge development, entrepreneurial experimentation*). The results, however, were mostly disappointing, but they continued developing the technology for a less advanced application in 1979−1982 (Asplund, 2009). VTT then established a cooperative partnership with the small company Perusyhtymä Oy (which later became known as Bioneer Oy). Instead of electricity production, their first commercial application was found in district heating

[260] An interest in pressurised gasification came from the chemicals company Kemira, which produced ammonia based on oil gasification near the town of Oulu. Plans were made to convert the plant to peat gasification but these were not realised until the following episode.

systems and in lime kilns (Kurkela, 1989).[261] Bioneer supplied the first commercial gasification plants to the market since the Second World War and by 1989 had sold ten units in Sweden and Finland with a capacity range of 1.5-6MW by (*materialisation*, *market formation*) (Kurkela, 1989).

Hence, by the beginning of the first episode a strong industrial structure existed in Finland consisting of capital goods suppliers, the institute VTT and the pulp and paper industry. By drawing on previous knowledge in fluidised bed combustion and on updraft gasification, the actors developed biomass- and peat-based gasification systems as an attractive alternative to the use of conventional oil in the lime kilns. The principal actors Ahlström, Bioneer and VTT conducted several *entrepreneurial experiments,* in collaboration and independently, which strengthened *knowledge development* and the actors gained commercial experience from the initial *market formation*. The customers, who were primarily within the pulp and paper industry, gained experience with the technology and, thereby, the functions of *legitimation* and *direction of search* of the TIS were also strengthened. Due to the existing market, resources could be mobilised internally by the incumbent firms but also from the government, which considered it strategically important to reduce oil dependency and increase the use of domestic resources (*resource mobilisation*).

The structure was strengthened through the strengthening of these functions. Of particular importance was the emerging science and technology infrastructure for developing the technology at Ahlstöm and VTT. However, an alignment between the technology, actors and institutions was not accomplished. Consequently, when the price of oil rapidly fell in 1986, further *market formation* was effectively terminated and this first episode came to an end.

8.2 Episode II: 1986–2003. Pressurised gasification, large-scale research programmes and the concentration of actors in Finland

Although some commercial actors identified gasification as an interesting technology during the first episode and reducing oil dependency was a prioritised goal of the government, the technology in itself was not deemed to be strategically important to the government. Public

[261] It has, however, been contested that the technology was useful in lime kiln and that it was only suitable for district heating (Anonymous 2, 2010).

policy was instead mainly focused on promoting CHP production in the district heating grid and increasing the competitiveness and use of domestic energy resources. As the future electricity demand was expected to be met by nuclear power, developing the pressurised gasification technology was, as above-mentioned, not seen as a realistic option (Kurkela, 1989; Asplund, 2009).

The Chernobyl accident in 1986 made the planning of the fifth and sixth nuclear reactors in Finland politically impossible to pursue, although the state-owned company Imatran Voima and the privately-owned company Teollisuuden Voima Oy (TVO) attempted to proceed with the plans anyway. These were finally stopped in 1992, when parliament adopted a resolution stating that nuclear power should no longer be a part of Finland’s future energy strategy (*direction of search*) (MTI, 1993; Stadsrådet, 1993).

With nuclear out of the picture, it became even more important to develop alternative domestic resources and technologies. It was deemed necessary to increase the power-to-heat ratio in cogeneration, since electricity consumption was increasing and the heat load in the district heating and process industry could no longer be expanded (Kurkela, 2002; Asplund, 2009). CHP production was based on a combination of peat, coal and some biomass and had a rather low electrical efficiency. Hence, there was room for improvement through technical progress and the introduction of biomass gasification to the system (Asplund, 2009).

At the time, the capital goods industry had reached a stage at which their empirical, trial and error approach to product development made it difficult to make further progress without having a better understanding of the underlying chemistry of the combustion and gasification processes (Hupa, 2008). In supplying power generating equipment, the capital goods industry had become an important export industry. Export revenues had increased and by 1992 were estimated to be €700-900 million. The Ministry of Trade and Industry (MTI) therefore identified the industry as strategically important to develop and wanted to improve its competitiveness even further (*direction of search*). The government set a target to increase exports to €1,800 million, which equalled the predicted total value of energy imports in 2000 (MTI, 1993).[262]

Consequently, an industrial policy was developed to provide the best possible conditions for exporting capital goods and placed an even greater emphasis on the development of technologies for energy conservation, the combustion of domestic fuels and the development of fuel supply from peat and biomass residues.[263] A central part of the Ministry of Trade and Industry's policy was the launch of ten new research programmes (*resource mobilisation*). The first programmes were initiated in 1988 and lasted for approximately five years.

Among the ten programmes, "Liekki" was the most significant for raising the level of scientific knowledge on combustion and "Jalo" for understanding the processes for fuel conversion (MTI, 1994a, b). It has been argued that with these programmes, a new research and development culture of industry-university collaboration emerged in Finland (Hupa, 2008). As many as 50 parallel projects could be pursued within Liekki, which was the largest programme. In each project, engineers from competing companies would work alongside scientists from VTT and the main universities. Collaboration between competitors was made possible because the programme focused on what they came to call pre-commercial research—which could potentially benefit all of the actors.

In these collaborations, the different actors took on different roles: VTT was primarily engaged in research on the various gasification processes and setting up experiments in their laboratories, the universities focused on the basic science behind the various processes and the capital goods suppliers focused on process development, patenting and commercialising the various results generated from the projects.

The programme was divided into two phases: 1988−1992 and 1993−1998. In these, the level of knowledge increased considerably and through this programme alone, the number of

[262] The value of the export market was estimated as 4-5 billion Finnish Marks (FIM) and the target was set to FIM 10 billion in the actual report published by MTI (1993). The value of a Finnish Mark in 1992 was approximately FIM 5.6 to €1. Source: http://www.oanda.com/currency/table, accessed 2010-06-08.

[263] The Finnish government devoted 80 percent of all research and development funding to energy efficiency and the development of energy conversion technologies based on domestic resources (MTI, 1993).

scientific experts on combustion and gasification went from approximately two individuals to more than 60 (*resource mobilisation*) (MTI, 1994b; Hupa, 1998, 2008).[264]

The new research and development programmes also significantly strengthened *direction of search* for pursuing electricity production based on gasification. With this new *direction of search,* the development of pressurised peat and biomass gasification for increasing electricity production became highly attractive to the incumbents, and they could continue strengthening the structure that already been developed during the first episode.

The actors engaged in various projects which will now be described. However, the first project to be realised in the context of pressurised bed gasification was not for electricity production, but for large-scale production of ammonia based on peat.

8.2.1 Kemira

One of the main actors that had been particularly interested in the pressurised technology as early as the 1980s was the state-owned company Kemira. The company owned an ammonia plant in the town of Oulu that it had desired to convert from oil to peat gasification ever since the second oil crisis. When Kemira finally decided to realise its plans in 1986, the price of oil fell. Although its interest waned somewhat, Kemira decided to pursue the project anyway.[265] This resulted in the first *market formation* for the pressurised technology.

The re-construction of the plant and research and development work involved was supported by the Jalo programme and joint research was carried out in collaboration with VTT. However, the Finnish actors had not chosen to pursue the pressurised technology during the first episode. As a result, there were no Finnish technology suppliers with access to the necessary technology and expertise for building the required plant (Koljonen et al., 1993). Instead, three foreign technology choices were evaluated by VTT and tested with Finnish peat. The evaluated options were the HTW process from Germany, the U-GAS process from the United States and the MINO process, which had been developed by Studsvik in Sweden. Kemira ultimately chose the German HTW process marketed by the

[264] Research and development in energy technologies at this point reached the same level as that in the other Nordic countries (Ericsson et al., 2004).

[265] The reason may have been that the project received significant support from the Jalo programme (MTI, 1994a).

large engineering firm Uhde. In retrospect, Uhde was probably chosen since it was the most experienced actor and the HTW process had been used in many similar coal installations before (Rensfelt, 2008). It was also judged to be the least complicated process and preliminary testing had demonstrated good results with peat (Asplund, 2009).

The re-construction of the plant was successful and the first ammonia based on peat gasification was produced in 1988. The plant had a thermal capacity of 42t/h ($80MW_{th}$) of peat with a moisture content of 40 percent, which was fed to the gasifier at 10 bars of pressure through a lock-hop system. Several test runs and changes were made before the production process could be stabilised. The total cost of the project has been estimated to approximately FIM 230 million (€38 million). In total, the plant accumulated 258 days of operation, but the use of peat was eventually terminated when the price of oil continued to drop to a level that made the plant's operation uneconomical (Koljonen et al., 1993).

From the perspective of Kemira and the government, which financed the construction and research and development work involved, the commercial experiment could be seen as a complete failure. However, one could instead think of it as an *entrepreneurial experiment* that significantly strengthened *knowledge development* and *materilisation,* and from which at least VTT was able to gain valuable experience. The project generated important insights, which may have been critical for allowing the Finnish actors to catch up with Studsvik, who had already gained experience with biomass-based pressurised systems (see Chapter VII).

Following the construction of the Oulu plant, the Finnish actors became interested in developing the pressurised BIGCC application. In addition to the "No to New Nuclear" campaign and the need to increase the power to heat ratio of CHP, the actors' interests were driven by the emerging debate on climate change (*direction of search*), which had reached the wider public through the "Bruntland Report" at the end of the 1980s (WCED, 1987). In response, in 1990 Finland became the first country in the world to introduce a tax on CO_2 emissions. A similar CO_2 tax was introduced in the Netherlands, Sweden, Norway and Denmark shortly thereafter (Vehmas, 2005). The introduction of the CO_2 tax was in a sense an *institutional alignment,* but the tax was very low and did not provide any real advantage to electricity production based on biomass gasification.

Hence, no “niche market” (Kemp et al., 1998) was created in which the technology’s poor price-performance ratio could be reduced through increased use and innovation. Instead, it was thought that further research and development through the Liekki and Jalo programmes would bring down the technology’s investment and operating costs. With some additional investment support, it was expected that the technology would become competitive with conventional alternatives. In the early-1990s, therefore, there were high expectations among the actors that the BIGCC technology would be commercially available by the end of the decade, without any major changes in the institutional context (Sipilä, 1993).

New projects were initiated as a response to these expectations. One of the first was launched at VTT in 1986, which strengthened the science and technology infrastructure by constructing a test facility for pressurised fluidised bed gasification (*knowledge development, entrepreneurial experimentation and materialisation*). The project was supported by Ahlström, Tampella, Imatran Voima, and the Swedish state-owned utility Vattenfall (Kurkela, 1989). Ahlström was very serious about developing the technology and devoted a large amount of internal resources to it (*resource mobilisation*) (Anonymous 1, 2009).

Ahlström’s main competitor, Tampella, was led by a visionary CEO who invested heavily in many new technology areas. Gasification was a priority, but a field in which they had no commercial experience. Instead of pursuing internal process development, Tampella decided to acquire a license for the U-GAS, pressurised BFB-process from GTI in the United States and constructed a 15-18MW_{th} pilot plant in Tampere. Both Ahlström and Tampella were looking for potential customers with which they could share the cost of further technology development and demonstrate the technology on a large-scale.

The three largest potential customers were the Finnish and Swedish utilities Imatran Voima, Vattenfall and Sydkraft, since these utilities were no longer allowed to pursue nuclear power (Äijälä and Huuskonen, 1993; see also Chapter VII). In particular, the Swedish utilities that had been able to push through a rapid expansion of nuclear power during the 1970s and 1980s (constructing 12 reactors) were under enormous pressure to demonstrate that they were developing alternatives (*direction of search*).

As a response to this pressure, the state-owned utilities Vattenfall and Sydkraft devoted significant internal resources to the effort (*resource mobilisation*). Vattenfall, for example, launched a €100 million programme to develop biomass-based energy resources, in which pressurised BIGCC was made a priority in the context of the VEGA project (see Chapter VII). The utilities also conducted their own separate preliminary studies on how best to pursue thermal conversion of biomass into heat and power. They arrived at the same conclusion: to maximise the output of electricity, biomass should be converted using pressurised IGCC systems. Of course, the problem was that the technology was not yet commercially available and there were very few technology suppliers with whom they could cooperate in developing it.

The most advanced knowledge of pressurised biomass gasification systems resided within Swedish and Finnish companies and research institutes. There were also a few US- and German-based actors with experience in coal gasification systems that could have been considered. In the process of selecting the best possible technology supplier, Vattenfall awarded preliminary studies to the Swedish constellation of Götaverken and Studsvik, as well as to Tampella (Vattenfall, 1991). In 1990–1991, both of the major Finnish actors Tampella and Ahlström were awarded contracts by the two Swedish utilities. Tampella received a contract for the VEGA project by Vattenfall and Ahlström for the Värnamo project by Sydkraft. These two projects will now be described from the Finnish perspective (cf. the Swedish perspective Chapter VII) before moving on to the restructuring of the Finnish capital goods industry that took place during the mid-1990s, and the failed attempts to build commercial-scale BIGCC demonstration plants in Finland. The second episode is concluded by describing two additional gasification projects undertaken by the Finnish actors.

8.2.2 VEGA and Värnamo

When Vattenfall came to an agreement with Tampella, a new company called Enviropower Inc. was created. All of the rights to the technology, including a pilot plant, were transferred to the new company, which was owned at 75 percent by Tampella and 25 percent by Vattenfall (Salo, 2008). Enviropower was awarded the contract based on a feasibility study for a commercial-sized, 60MW_{el} BIGCC demonstration plant to be located in Eskilstuna, Sweden. Furthermore, a test and verification series was financed by Vattenfall to be performed at the pilot plant in Tampere and in the smaller laboratory gasifier at VTT in Helsinki (*knowledge development and entrepreneurial experimentation*) (Vattenfall, 1994). From 1991 to 1995, 1,630 tonnes of wood chips, 1,750 tonnes of forest residue, 1,180 tonnes of paper mill waste (including bark, paper and sludge), 400 tonnes of willow, 20 tonnes of straw (together with 120 tonnes of coal), and 120 tonnes of alfalfa stem pellets were gasified (Kurkela, 2002). Despite extensive testing, knowledge and technology development, the feasibility study never resulted in an actual plant being built in Eskilstuna. During summer 1992, just two years after the collaboration with Tampella was initiated, the feasibility study was terminated and no investment decision was made. However, Vattenfall decided to continue with the test and verification programme until it was completed in November 1994 (Vattenfall, 1994). When Vattenfall decided to withdraw from Enviropower Inc, it went bankrupt (Salo, 2008).

The Executive Committee at Vattenfall considered the large investment volumes and the power balance in the Nordic countries as the primary reasons for not constructing the demonstration facility (Vattenfall, 1994). The manager of the VEGA programme, Birgit Bodlund (1998), argued that the technical risk would be too great for Vattenfall. In 1995, it was estimated that a commercial-sized demonstration plant would had cost about €100 million, but no funding schemes were available to off-load the risk to Vattenfall (see Chapter VII).

The second project between a Swedish utility and a Finnish capital goods supplier was that between Sydkraft and Ahlström, who decided to form a joint venture company called Bioflow, to develop and market the BIGCC technology based on Ahlströms previous experience (Ståhl, 2008; Jönsson and Tillberg, 2009). Sydkraft's goals were somewhat different from Vattenfall's; their priority was to demonstrate the technology in a fully integrated facility at the lowest possible cost—not to demonstrate the highest possible efficiency of the technology on a commercial-scale (Ståhl, 2008; Sydkraft, 1997).

Approximately 70 percent of the total cost of construction, or €23 million, was financed by Sydkraft and the remaining part (€7 million) was funded by the Swedish government (*resource mobilisation*). Construction began in March 1991 and was completed, after some delays, in 1993. However, several problems occurred and the plant could not be brought into full operation until 1996 (Sydkraft, 1997, 2000).

Upon completion of the plant, Ahlström became the first actor with the experience of constructing a large-scale pressurised IGCC plant specifically designed for using biomass. Having taken part in the development work of both the VEGA and Värnamo projects, VTT reinforced its already strong position as perhaps the world's leading research organisation for biomass gasification.

However, in order to attain the high electrical efficiencies that everyone was hoping for (about 40-45 percent in CHP mode), at least one large-scale, fully integrated demonstration facility would have to be built.[266] In addition, a new type of turbine would have to be developed, designed specifically for the low calorific biomass-based producer gas. So far, the turbine manufacturers have been reluctant to devote resources to this, as well as to participate in research and development projects that may result in such modifications, even though it is likely that only relatively small changes will need to be made (Horazak, 2007b; Nyström, 2007; Kurkela, 2008; Salo, 2008). However, neither Sydkraft nor Vattenfall were interested in realising such a plant. Instead, the Finnish capital goods suppliers could only hope that potential customers in Finland would realise their plans. Before continuing with a description of those plans and assessing the potential of realising a large-scale demonstration of the technology in Finland, it is necessary to review the restructuring of the Finnish capital goods industry that took place in the mid-1990s.

8.2.3 Restructuring of the Finnish capital goods industry and the potential for demonstrating BIGCC in Finland

When the VEGA project was terminated, and just before the construction of the Värnamo facility was completed, a major restructuring of the Finnish capital goods industry took place. It began when Vattenfall pulled out of Enviropower, forcing the small company with about 50 personnel to go bankrupt. This resulted in the formation of a spin-off company, Carbona,

[266] It has been argued that more than 30 plants would have to be built for the technology to be commercially competitive with conventional alternatives without any further support schemes (Claeson Colpier, 2009).

consisting of 10-15 of the core individuals with gasification experience. Carbona subsequently received a sub-license for the pressurised BFB technology that had been piloted in Tampere (Salo, 2008; Isaksson, 2009).

The mother company, Tampella, was eventually forced into bankruptcy. It was then acquired by Kvaerner, which had already acquired the Swedish capital goods suppliers Götaverken, Generator, Kamyr and Chemrec (for developing black liquor gasification). Biomass gasification was, however, not a priority for Kvaerner, and the remaining gasification experts at Enviropower were given other types of positions at the company and the pilot plant in Tampere was mothballed (Salo, 2008; Isaksson, 2009).

In 1995, a second major structural change took place when two divisions at Ahlström were sold to the two multinational capital goods suppliers Foster Wheeler and Andritz. With the acquisition, the gasification competencies at Ahlström were divided between the two companies. The lime kiln related gasification technology became an integral part of Andritz and other gasification technologies (pressurised and atmospheric) became part of Foster Wheeler (Kurkela, 2008; Palonen, 2008; Salo, 2008). Both divisions were located in the small town of Varkaus, in central Finland.

It was not self-evident that the multinational corporations, particular Kvaerner, Foster Wheeler and Andritz would keep the research and development departments in the relatively small, remote and sparsely populated Finnish towns of Tampere and Varkaus. In addition, it was probably even more unlikely that they would concentrate their research and development efforts and sales activities within the relevant areas on these locations. For Foster Wheeler the question was whether research and development for CFB boilers should be moved to the United States or remain in Finland (Hupa, 2008).

A the time, Professor Hupa was head of the Liekki research programme and took part in presenting the knowledge base within the field to the management at Foster Wheeler. According to Hupa (2008), the management team at Foster Wheeler was impressed by the elevated level of knowledge and could not find the corresponding expertise in the United States. It has therefore been suggested that the ten research and development programmes initiated by the Ministry of Trade and Industry strongly contributed to making Finland an attractive location for the multinationals to concentrate their research and development activities (Hupa, 2008).

By the mid-1990s three major capital goods suppliers, Kvaerner, Foster Wheeler and Andritz, and one smaller supplier, Carbona, were located in Finland. These firms had the experience and capacity necessary to build various types of gasification plants. In addition, VTT was perhaps the world's leading research institute on biomass gasification. Several research departments at Åbo Akademi, Helsinki University of Technology and the University of Tampere, had significantly increased their knowledge on the chemical processes of combustion and gasification through the various research programmes, pilot and commercial projects.

Hence, in 1996 and after the Värnamo facility was completed, the Finnish structure was among the most advanced in the world with regard to pressurised gasification systems. In addition, management at Foster Wheeler had a list of customers who were interested in such plants. Before the market could be realised, however, it was necessary to construct at least one large commercial demonstration for reducing the remaining technical risks of the technology (Palonen, 2008).

It would have made clear sense to build such a commercial demonstration plant in Finland. The capital goods industry would benefit from a first market, Finland has large district heating systems, and a pulp and paper industry with which the technology could be integrated and there was a growing demand for new electricity production that had high electrical efficiency and could utilise the existing heat sinks. Some steps towards realising a commercial demonstration were also taken.

The utility Imatran Voima and actors within the pulp and paper industry, such as Enso and Metsäliitto, had been awaiting the result from the experiments that were taking place in Sweden and had made their own preliminary studies on commercial-sized plants, either integrated in a district heating system or in a pulp and paper plant. The Imatran Voima study concluded, however, that a commercial demonstration would not be possible without significant investment support (Äijälä and Huuskonen, 1993).

Tampella (Kvaerner) and Foster Wheeler had two projects with Enso and Metsäliitto respectively. The decisions to invest were almost taken at the mills in Summa and Äänekoski. The firms had applied for investment supports to construct two $60MW_{el}$ BIGCC plants. They were offered 25 percent of the investment cost as well as some employment support, but the customers did not consider this to be sufficient (Asplund, 2009). Instead it was argued that 35-40 percent of the investment cost would have been (and still is) necessary to realise a first commercial-scale demonstration of this type (Salo, 2008).

So far, such high levels of investment support have not been available in Finland, and there have been no real attempts by the actors to align the institutional framework in such a way that would allow for such volumes. It has also been argued that the price of heat in Finland and Sweden is relatively high compared to the price of the electricity, which makes it unattractive to invest in technology with higher power output ratios. It would, therefore, make more sense to develop the technology for warmer countries where the price of electricity is higher in relation to heat; such countries, however, usually lack sufficient heat sinks.

Hence, the next step towards developing BIGCC was never taken in Finland (or anywhere else in the world). The decision to mothball all further BIGCC projects seriously weakened the *legitimacy* of the technology and put an end of all further *market formation* activities for BIGCC. Consequently, Kvaerner (former Tampella) and Andritz withdrew from the market, but continued to participate in research projects (Isaksson, 2009). Carbona tried to continue to develop the market, but had a very difficult time finding any new projects to pursue at all (Salo, 2008).

In retrospect, it is not difficult to understand why the capital goods and pulp and paper industries hesitated to pursue the technology further. Towards the end of the 1990s, many of these actors struggled with financial difficulties, and pursuing a completely new technology with high investment costs and high risk of technical failures is not a very attractive option in such a situation, particularly given the level of the available investment subsidies. Few new investments were made in energy technology at all towards the end of the 1990s due to ongoing deregulation of the European energy markets. The deregulations created uncertainties around future market conditions, dampening investors' willingness to pursue risky new technology development projects.

Although they did not actively pursue further projects, the capital goods suppliers were able to maintain their levels of competence due to the ongoing research programmes on combustion and gasification (Isaksson, 2009). In addition, Foster Wheeler and VTT could maintain and also develop their competencies in the field by taking on new commercial projects. These projects were, however, on applications that were less advanced than BIGCC, and were focused on using more difficult fuels. The projects will be described in the following section.

8.2.4 Project pursued by Foster Wheeler and VTT

In 1998, Foster Wheeler supplied an CFB gasifier to the Kymijärvi Power plant in Lahti (*entrepreneurial experiment* and *market formation*). The gasifier was of the same type of atmospheric lime kiln gasifier developed by Ahlström in the first episode, but in combination with simple gas cleaning. The plant connects to an existing coal-fired boiler in which the producer gas is fired, replacing approximately 15 percent of coal consumption. The gasifier utilises roughly 300GWh annually and has a capacity of 40-70MW_{th} depending on the moisture content and heating value of the input fuel. The fuel used is a combination of solid biofuels, sorted house-hold waste, and industrial refused-derived fuels from the Lahti area, which are all mixed together. Since the new plant could be integrated into the existing infrastructure, the cost of the gasification system could be limited to €12 million, for which €4 million was granted from the EU Thermie Programme (Kivelä and Takala, 2009). A second plant of the same type was later delivered to Electrabel in Belgium for the same purposes, although the operator uses pure biomass in the plant in order to qualify for green certificates.

In 2001, yet another *entrepreneurial experiment* was completed when a first commercial-sized BFB gasifier was constructed in Varkaus. The 40MW_{th} gasifier utilises plastics and aluminium containing rejected materials that are by products of the recycling process for used liquid cartons. In the process, aluminium is removed from the gas and recycled, while the producer gas is combusted in a steam boiler, replacing fuel oil in the Stora Enso's power plant in Varkaus (Kurkela, 2002). The main development work was undertaken by VTT and its customer Corenso United Ltd. Foster Wheeler constructed the plant, but even though the plant continues to be in operation, it believes that the design will probably be the only one of its kind since the process is quite complicated (Palonen, 2008). Nevertheless, the TIS was strengthened, and the above-mentioned projects particularly strengthened the functions of *knowledge development, entrepreneurial experimentation* and *materialisation* as well as *market formation* for the less advanced applications.

After the completion of the two plants, interest in gasification waned and remained quite low until the beginning of 2003, although it did not stop completely. Some activities continued at VTT, such as experimenting with small-scale electricity production based on gasification. VTT and Lahti Energia also sought ways to further explore waste gasification. Initial tests were carried out in collaboration with VTT, illustrating that 100 percent pre-sorted household waste could be used and, with some additional gas cleaning, a stand-alone unit could be built with significantly higher electrical efficiency compared to conventional waste incineration (Kurkela, 2008; Kivelä and Takala, 2009).

Lahti Energia wanted to proceed with the new opportunity that had emerged in collaboration with VTT. As its existing coal-fired boiler was getting old and it wanted additional capacity, Lahti Energia was interested in building a new stand alone 160MW_{th} (50MW_{el}) plant, designed for 100 percent gasification of pre-sorted household waste combusted in a separate boiler (Kivelä and Takala, 2009).

Hence, due to the activities undertaken by VTT and Lahti Energia, two possible business opportunities for waste gasification opened up for Foster Wheeler. First, it could continue developing waste gasification where the gas would be co-fired with coal in existing boilers and, second, it could develop the stand alone waste gasification process with considerably higher electrical efficiency than conventional waste incineration.

To realise these potential markets, two prominent issues had to be resolved. The first concerned whether co-firing with a gas derived from pre-sorted household waste would turn the entire coal plant into a waste incineration plant, which would then have to be operated under the EU waste incineration directive. The matter is of great importance, since old coal plants would never be able to be fulfil the waste incineration directive, which would effectively eliminate the business opportunity (Kivelä and Takala, 2009).

The second issue was that a first stand alone commercial-scale demonstration facility would have to be built and successfully operated in order to secure the interest of subsequent customers. Lathi Energia was interested in being the first customer for such a plant, and was able to obtain a 10-20 percent investment subsidy from the EU and the Finnish government (Kivelä and Takala, 2009).

However, a set of delays caused considerable problems for Lahti Energia. The capital goods supplier, Foster Wheeler, was at first hesitant to develop the opportunity due to the difficult regulatory environment and protests against the stand alone plant (Palonen, 2008). With time, they became even less interested and eventually declined the offer to construct the plant, even though environmental permits were finally granted (Kivelä and Takala, 2009).

The main reasons for this can be found in the third and final episode of biomass gasification, in which interest in transportation fuels emerges also in Finland. The firms with competencies in biomass gasification were once again in short supply and most of the research and development resources at Foster Wheeler became tied up in new promising projects for converting forest residues into high value transport fuels (Kurkela, 2008; Palonen, 2008; Kivelä and Takala, 2009).

In summary, the second episode commenced with the falling price of oil and the 1986 Chernobyl accident. The accident provided a new *direction of search* that was later reinforced by the emerging debate on climate change, as well as the recognition of the increasing importance of the national capital goods industry's capacity to produce and export power generating equipment. The new *direction of search* resulted in an institutional change in which 10 new research programmes were created, and investment support as well as a CO_2 tax were introduced to support the development of renewable technologies. Attention was, directed towards large-scale electricity production of biomass and peat with high electrical efficiency compared to conventional combustion. However, no niche markets were created for the technology. Rather, it was expected that further research and development and some investment support would drive down the costs associated with the immature technology to the levels of conventional electricity production.

The research programmes contributed to *resource mobilisation* and were designed to enhance the competencies of Finnish industry and make domestic resources competitive compared to fossil fuels and nuclear power. Among the programmes, Jalo and Liekki were directly aligned with the field of gasification and enabled the actors to significantly strengthen *knowledge development, entrepreneurial experimentation* and *materialisation*. It is likely that the Jalo and Liekki programmes also contributed to strengthening *market formation* in terms of a first attempt at pressurised gasification in Oulu, Finland.

With the experience from Oulu and the research programmes, the Finnish actors managed to catch up with their US, German and Swedish competitors in the field of pressurised gasification. Their position was further advanced when the two most prominent capital goods suppliers, Tampella and Ahlström, were selected by the Swedish utilities Vattenfall and Sydkraft to proceed with major demonstration projects. This further strengthened the functions of *resource mobilisation, knowledge development, entrepreneurial experimentation,* and *materialisation,* as well as the actor and technology structure in the Finnish TIS of biomass gasification.

The major Finnish capital goods suppliers were acquired by the large multinationals Kvaerner, Foster Wheeler and Andritz during the mid-1990s. However, even though Kvaerner and Andritz eventually withdrew from the field of gasification, the main research and development activities of the multinationals remained and concentrated to Finland. This related to the high level of resident knowledge in the country, which had been developed through research and development programmes and many market activities in combustion as well as in gasification. In addition, by the end of the episode, VTT had probably become the most experienced institute in the world with regard to fluidised bed biomass gasification. However, although the conditions for realising commercial-scale BIGCC were excellent in Finland, this was not achieved mainly because the level of available investment subsides was too low.

The competencies in biomass gasification at Kvaerner and Andritz were maintained through their participation in various research programmes. In addition, Foster Wheeler and VTT pursued a few less advanced applications and a potential market for waste gasification emerged as a result. However, after completing two plants by 2001, no new projects were pursued and the episode came to an end. Interest in biomass gasification remained low until 2003, when interest in the production of renewable transportation fuels made biomass gasification a technology worth exploring.

8.3 Episode III: 2003-2009. An emerging interest for second-generation transportation fuels from biomass

Historically, the interest in increasing the share of renewable liquid fuels in the transportation sector has been very weak in Finland. Not even during the 1970s and the oil crises had any serious attempts been made to produce such fuels from gasification. There has been no domestic production of first-generation renewable transportation fuels in Finland, and the agriculture industry has not made it a priority to promote them.

EU Directive 2003/30/EC provided a mandate for increasing the share of biofuels in the transportation sector in all EU member states. The directive set targets for each state to increase their share of biofuels to 2 percent by 2005 and 5.75 percent by 2010. Moreover, it encouraged actions to be undertaken for developing domestic resources for increasing the production of biofuels (EC, 2003).

At the time of the directive’s adoption, the share of biofuels in Finland was 0.10 percent, as compared to 0.13 percent in Austria, 1.33 percent in Germany, 1.07 percent in Sweden and the EU-25 average of 0.49 percent (Eurostat, 2009). The directive encouraged member states to take actions to increase their share of biofuels, and as a result the EU average increased from 0.49 to 1.08 percent by 2005. However, only Germany and Sweden managed to reach the 2 percent target.

In Finland, commitments for reaching the targets set within the EU framework are usually made, but with no ambition of exceeding them (Hildén, 2008). Government policy has been dominated by avoiding all costs that such policy can impose on the incumbent industry. The government has argued that Finland is too small to take the lead in climate and environmental protection. Instead, the strategy to curb increasing CO_2 emissions has been to increase the amount of nuclear power through the construction of a fifth and perhaps sixth reactor (MTI, 2005; Hildén, 2008). A national target was eventually set to maintain the 0.10 percent share of biofuels in transportation fuels. By 2005, that share had decreased to 0 percent (MTI, 2005; Eurostat, 2009).

Although the Finnish government provided no response to the EU directive, Finnish industry was quick to realise that a huge market for renewable fuels was under development. The first actor to react was the Finnish oil refining company, Neste Oil. Neste Oil had a common history with Fortum, which had been created through the merger of the state-owned utility Imatran Voima and Neste Oil in 1998. Just seven years later, Neste Oil was spun-off as an independent company (Kaikkonen, 2008).[267]

Neste Oil saw that the directive had created a niche market for innovative renewable products in which a smaller refinery corporation with a high technical standards (such as itself) could find competitive advantage over larger refineries (Kaikkonen, 2008). From Neste Oil's perspective it made sense to react quickly to the opportunity, and it decided to explore two possible routes towards renewable fuels.

First, Neste Oil developed a process for hydrating vegetable oils and animal fats (NExBTL) to produce a diesel fuel that can be blended with ordinary diesel in any quantity. It soon realised that even though the process was far more promising than the production of first-generation fuels from wheat, corns and soya, the feed-stock was in limited supply and could not generate any significant volumes in the future (Kaikkonen 2008). In addition, Neste Oil came to be heavily criticised for its use of palm oil in the hydration process (*legitimation*).

Second, in 2003 Neste Oil did some preliminary work with VTT to explore the possibilities of biomass gasification for producing transportation fuel. However, they concluded that it was too early for an industry-driven project (Kurkela, 2008). Instead, VTT initiated a three-year research and development programme called "Ultra Clean Gas" (UCG) with a total budget of €4 million (*resource mobilisation*) and which commenced in January 2004 (Kurkela, 2008).

[267] http://www.nesteoil.com, accessed 2009-08-11.

Helsinki University of Technology also participated in the research activities and TEKES provided a total of €846 000 in funding for the project. As a result, an initial industry consortium could be created consisting of Foster Wheeler, Neste Oil, Andritz and the utility firm Vapo with a strong focus on bio-energy (Kurkela, 2008).[268] The project led to the construction of a 500kW process development unit (PDU) at VTT, and system studies were carried out (*knowledge development, entrepreneurial experimentation, materialisation*).

The studies suggested that the technology would be most efficiently integrated in the pulp and paper industry. The industry was thus invited to participate in the project and UPM, StoraEnso, M-real, Botnia, and the utility PVO joined the industry consortium shortly thereafter (Kurkela, 2008).

The pulp and paper industry had, at the time, strong incentives for joining the ongoing development project. Since 2000, the entire industry had been in deep crisis as a result of increased energy prices, export tariffs on wood from Russia, increased competition from Brazil and other countries with access to a faster growing forest than in the Nordic countries and production overcapacity in the European market (Sohlström and Helin, 2008; Donner-Amnell, 2009; Gädda, 2009; Isaksson, 2009).

Historically, the industry has met increased competition from southern forests through mergers, acquisitions and moving towards higher value paper products (Donner-Amnell, 2000, 2009). Today, however, it is very difficult to identify higher value paper products. Besides, during the end of the 1990, when the electricity market was undergoing deregulation, some of the pulp and paper firms had sold their power production capacity located at the mills to the power utilities.[269] While the firms who kept their own capacity for electricity production were in a better position than those who did not, they were still desperately trying to find higher value use for the residues from the papermaking process.

[268] http://akseli.tekes.fi/opencms/opencms/OhjelmaPortaali/ohjelmat/ClimBus/en/system/projekti.html?id=8810332&nav=Project, accessed 2010-08-04.

[269] The idea behind the strategy was that they should focus on their "core business" (pulp and paper production) and not on power generation. It was expected that in a deregulated market, the prices would go down and not up. A few years later, when electricity prices had significantly increased, they had arrived at a situation in which they had to cover their electricity demand by acquiring everything on the market and selling their forest residues to the utilities at what they considered a very low price (Englund, 2008).

The production of high value renewable transportation fuels and other chemicals fits relatively well into the business model of the pulp and paper industry. It is a large-scale, process-oriented, business-to-business activity and could improve the conditions for making paper in northern countries (Donner-Amnell, 2009; Gädda, 2009). However, the industry is also very conservative and in the absence of crisis, it is unlikely that they would have become involved in the production of transportation fuels and chemicals (Donner-Amnell, 2009; Gädda, 2009).

The UltraClean Gas project was, therefore, not only critical for strengthening various functions of the TIS in Finland. Perhaps more importantly, it became an important node in the network that enabled the formation of two major Finnish industrial alliances with the goal of realising the production of renewable transportation fuels and other high value chemicals on a large-scale.

To start with, Stora Enso and Neste Oil teamed up and created the joint venture company NSE Biofuels Oy in 2006. The joint venture has since then contracted Foster Wheeler to take part in the technology development and to construct a larger demonstration facility. VTT has also been contracted as a preferred partner for testing and research (Jokela, 2008; Kaikkonen, 2008; Palonen, 2008).

The demonstration plant was designed as an atmospheric 12MW_{th} lime kiln gasifier located at Stora Enso's pulp and paper mill in Varkaus. During the demonstration phase, the gasifier will be operated with oxygen and steam as a gasification agent at atmospheric pressure. The gas flow will be divided into two streams. In one of these, 5MW of the gas will be cleaned and part of that to "ultra-clean" gas levels. The clean gas will then be tested for FT-production, diverted back and consumed in the lime kiln. It has been argued that the actual wax or liquid production at the scale of 5MW is not necessary—as such it will not be a part of the project. However, based on the slip streams, various FT catalysts will be tested (Jokela, 2008; Kaikkonen, 2008; Palonen, 2008).

The size of the demonstration facility and the gasifier corresponds to the gas requirements of the lime kiln at the mill. Hence, the demonstration carries most of its own operating costs. In addition, the investment makes sense beyond the demonstration alone, since if the oxygen and additional cleaning systems are removed, the gasifier can be operated as a normal lime kiln gasifier (Jokela, 2008).

The total budget was set at approximately €40 million during the demonstration phase, including investments as well as research and development work. Out of the total sum, the Ministry of Employment and the Economy (formerly MTI) supports the investment with €7 million and TEKES supports the project by funding 50 percent of the research and development activities. The remaining sum is covered by Neste Oil and Stora Enso on equal terms (Jokela 2008; Kaikkonen 2008). The demonstration facility was inaugurated in June 2009 (Stora Enso, 2009).

The second alliance to emerge in Finland as a result of the Ultra Clean Gas project at VTT consists of UPM and Andritz. However, in this case no joint venture company has been created and UPM remains the principal actor in the project. The role of Andritz is that of a partner in technology development and it will profit from the construction of such plants in the future (Anonymous 1, 2009).

The gasification competencies at Andritz originate from the acquisition of Ahlstrom's division for pulp and paper machinery in Varkaus, which had constructed the atmospheric lime kiln gasifiers during the first episode.[270] However, in order to realise BtL production within the context of the cooperation agreement, the gasification competencies at Andritz would have to be significantly strengthened.

For that purpose, Andritz approached Carbona, the company created when Tampella and Enviropower went bankrupt in the mid-1990s. Carbona had since the 1990s been working on various gasification projects. Most importantly, they had realised a project in the town of Skive, Denmark, where they had constructed a 12MW_{th} BFB gasification plant, connected with gas engines for combined heat and electricity production. In addition, Carbona was perceived as attractive since it has a longstanding and, for Andritz, important collaboration

[270] In 2003, Andritz decided to market their atmospheric lime kiln gasifiers when the price of oil began to increase. Consequently, it received a few major proposals for the project. Due to the financial crisis in 2008, however, none of them have been realised (Anonymous 1, 2009).

with the Gas Technology Institute (GTI) in Chicago,[271] with whom it developed the BFB technology piloted in Tampere by Enviropower in the previous episode.

For Carbona such a collaboration was also attractive, as it was a rather small actor that had difficulties taking on large-scale projects and securing financial guarantees (Salo, 2008). Therefore, Carbona eventually came to an agreement with Andritz (Salo 2008).

The first steps towards realising the plans for BtL production were taken in 2005 by rebuilding the pressurised IGCC pilot plant in Chicago for BTL purposes. The plant is a 5MW_{th}, oxygen-blown, pressurised BFB pilot plant. GTI has also been contracted for further testing and research on the pilot. By combining the experience from the pilot plant with Carbona's experience from Skive, the alliance has expressed that they will scale up the technology directly to a commercial-sized demonstration plant in the range of 3*150MW_{th} at a UPM mill site, beginning no earlier than 2011 (Salo, 2008; Sohlström and Helin, 2008).[272]

Production of FT liquids or waxes, as well as the testing of different FT catalysts, has not been announced as part of the pilot and the development project. Rather, the FT process is viewed as an off-the-shelf technology that can be contracted once the commercial plants are built (Sohlström and Helin, 2008).

UPM is the project owner and is responsible for funding all of the development work in Chicago. In total, it has invested €10 million in the pilot phase. UPM has also invested €50 million developing a new type of dryer that can handle the volume of biomass residues required for a commercial-scale plant. For a full-scale plant of 200,000 tonnes liquid production, UPM has estimated the cost to be €300-400 million. According to Hans Sohlström (2008), Director of New Businesses and Biofuels, UPM will be prepared to take the lead in such a large investment even if it will be looking for partners.

The third Finnish technology supplier to become seriously interested in biomass and waste gasification during the third episode is Metso Power. Metso was created through a merger

[271] For UPM and Andritz, collaborating with VTT on technology development was viewed as out of the question. It was argued that VTT is the best institute for biomass gasification in the world, but for realising BtL production, it was seen as too closely affiliated with the competing team (Salo, 2008).
[272] The 12MW Skive plant is operated at 2 bars of pressure, and its cleaning equipment is the same size as that for a commercial-sized (150MW) BtL plant operating at 15 bars of pressure.

of Rauma and Valmet in 1999. Valmet had, in 1992, acquired Tampella Paper Machinery while Tampella Power had been sold to the Norwegian company Kvaerner. Kvaerner had also acquired the Swedish boiler manufacturer Götaverken, in 1991. In January 2007, Metso acquired Kvaerner’s pulping and power businesses. As a result, Metso attained access to the previous experience and the reference plants of both Götaverken and Tampella Power (Isaksson, 2009).[273]

However, the main interest for Metso has not been in developing gasification for the production of renewable transportation fuels or other chemicals. Instead, it picked up the Lahti waste gasification project when Foster Wheeler declared that it was no longer interested (Isaksson, 2009). When the necessary environmental permits had finally been granted, Metso Power was asked to take over the project.

Metso was interested in the technology because it was identified as an application that was closer to reaching the market than renewable fuels. It was also argued that it is possible to create a market for the technology that does not depend on future state subsidies and investment support once it is demonstrated on a commercial-scale (Isaksson, 2009). Since then, Metso has mobilised significant resources to develop the business opportunity. It initiated a test campaign with gas cleaning equipment, both at the lime kiln gasifier at the Värö paper mill in Sweden (which was built by Götaverken during the early 1980s) and at the waste gasifier in Lahti. VTT has also been involved in testing and research on the technology (Isaksson, 2009).

In November 2009, Lahti Energia took an investment decision to start constructing the plant. The construction project will receive €7 million in financial aid from the EU and €14 million from the Finnish government. The total project has been valued at €157 million (Lahti Energia, 2009). Meanwhile, in planning for Lathi II, Mälardalen Energi of Sweden has sought proposals for a similar but larger plant. It aims to construct a 200MW plant through a project valued at approximately €220 million (Isaksson, 2009).

[273] At the time, Carbona was also in discussions with Metso Power in parallel with Andritz. In a way, collaboration between them would have been more natural due to their common origins.

More recently, Metso has expanded its interest in producing renewable transportation fuels, and participating in the Gobigas project in Sweden and collaborating with Chalmers University of Technology on the development of indirect gasification (see Chapter VII).

8.4 Summary of Episodes I-III: The evolution of fluidised bed gasification in Finland

The first episode was dominated by the oil crisis, which encouraged the manufacturers of capital goods for the pulp and paper industry and VTT to start experimenting with atmospheric gasification for oil substitution in the lime kilns, district heating and relatively small-scale electricity production with gas engines. The technology co-evolved with the development of fluidised bed combustion, an area which Finnish actors became very strong.

For gasification, a commercial application was found in lime kilns for which the need for gas cleaning was modest. Electricity generation, on the other hand, requires more advanced gas cleaning which limited the diffusion to a few pilot installations. Conceptual studies on pressurised systems were undertaken, but the technology was seen as too complicated and expensive to pursue, especially since the future of electricity generation was expected to come from nuclear power.

It was not until the beginning of the second episode that interest in pressurised gasification took off. Due to the Chernobyl accident and increased awareness of climate change, the *direction of search* changed in favour of large-scale electricity production. However, the first project to be realised was for ammonia production. Since no Finnish actor had experience with pressurised gasification from the previous episode, the German capital goods supplier Uhde was contracted and the ammonia plant owned by Kemira was rebuilt for peat gasification. VTT took part in the development process and was able to learn from the experience, even though peat gasification was terminated after just 258 days of operation.

The Finnish capital goods suppliers Ahlström and Tampella identified BIGCC as an important technology to pursue and started developing it in collaboration with VTT. They also started looking for customers, but the utility Imatran Voima and the pulp and paper industry were reluctant to participate. Instead, the first contracts were signed with the Swedish actors

Vattenfall and Sydkraft, who were being pressured by the Swedish government to develop alternatives to nuclear power.

Through mainly these three projects, VTT and the capital goods suppliers were able to "catch up" with the Swedish actors who had already experimented with pressurised systems during the first episode. The development was supported by the Ministry of Industry and Trade that launched ten large-scale projects with the purpose of increasing the level of knowledge in industry with regards to combustion, gasification and fuel conversion, and to develop domestic energy resources. Through these projects, collaboration between the capital goods suppliers, VTT and the universities was further strengthened. In these collaborations, VTT primarily took on the role of research on process development and setting up large-scale laboratory experiments; the universities focused on the basic science behind the various processes; and the capital goods suppliers focused on patenting and commercialising the various results generated from the projects.

Through the research programmes, in combination with laboratory experiments and large-scale semi-commercial projects such as Oulu, Värnamo and VEGA, the actors considerably strengthened *resource mobilisation*, *knowledge development*, *entrepreneurial experimentation*, *materialisation, legitimation, direction of search* and, to some degree, *market formation* for less advanced applications. By strengthening the above-mentioned functions, the actors also strengthened the structure of the TIS. The number of experts on thermal conversion of biomass increased from about two individuals to over 60 through one of the major programmes alone (Liekki). Hence, the level of knowledge of the existing actors increased considerably—not just in gasification but in several complementary fields. In addition, an advanced science and technology infrastructure was developed, which was of great importance to the future survival of the capital goods industry in Finland.

Hence, by the mid-1990s, when a major restructuring of the Finnish capital goods industry took place, the technology and actor structure of the TIS for both combustion and gasification was very strong in Finland. As a result, instead of moving important research and development activities to other countries, multinational capital goods firms—such as Metso Power, Andritz and Foster Wheeler—have since concentrated their activities in Finland.

Even though MTI was successful with the research and development programmes, it was unsuccessful in creating the conditions for realising the first commercial-scale demonstration plant in Finland. The basic idea had been that research and development, in combination with investment subsidies in the range of 20 percent, would be sufficient for making the technology commercially interesting. This was, however, insufficient.

There were no attempts to achieve a stronger institutional alignment in order to create a niche market for the technology. Consequently, interest in BIGCC tailed off and no commercial-scale demonstration projects were realised, even though the preconditions in Finland were probably better than anywhere else in the world. Foster Wheeler and VTT did, however, continue developing waste and biomass gasification in combination with boiler technology for combined heat and power generation, and the level of knowledge in the field was maintained through the various research programmes.

Interest in biomass gasification once again picked up in 2003, when the *direction of search* shifted towards the production of renewable transportation fuels due to EU Directive 2003/30/EC. Prior to 2003, interest in biofuel had been very low and the government had developed a late adopter approach to all new environmental and climate regulations imposed by the EU. However, the main refinery company in Finland, Neste Oil, identified gasification as an interesting technology option for developing the large-scale production of renewable fuels. Together with the capital goods suppliers and VTT, a research project was initiated to explore the possibilities with the technology. They soon came to the conclusion that the technology would be best integrated into the pulp and paper industry, which was also invited to participate in the project.

The pulp and paper industry, which had been in a deep crisis since the turn of the century, was in dire need of finding new high value products and markets into which they could expand. The production of renewable fuels from low value residues from the papermaking process appeared to provide such an opportunity. Based on the existing industry structure, two competing teams were established to further explore biomass gasification for FT diesel production in Finland.

In addition, Metso Power has continued working on waste gasification and is in the process of constructing the first commercial-scale standalone plant in the town of Lahti. More recently, it has also started taking steps towards BioSNG production through collaborative projects with Chalmers, Göteborg and Repotec (see Chapter VII).

8.5 The system builders' transformative capacity, system weaknesses and the potential role of policy

In this section, the four research questions specified in Chapter II will be revisited. Answers to each question will be provided for the case of Finland by analysing the previously outlined history of fluidised bed gasification. The research questions were formulated as:

1) *Who act as system builders in the different national contexts?*
2) *What characterises the nature and extent of the system builders' transformative capacity?*
    a) *How do the system builders make use of the general structure in which they are embedded to form or strengthen the structure and the various functions of the TIS?*
    b) *To which extent do the system builders manage to strengthen the structure and functions of the TIS?*
3) *What are the limits to the system builders' transformative capacity and how can these be explained?*
4) *Given these limits, which system weaknesses remain to be resolved by system builders and policymakers on different levels (national and EU)?*

This section is divided into two main parts. Research Questions I and II will be analysed in the first part, which will start by identifying the system builder and discuss the nature and extent of the system builders' transformative capacity. In the second, the focus shifts to explaining the limits of the system builders' transformative capacity and the potential role of system builders and policymakers in resolving these.

8.5.1 The nature and extent of the system builders' transformative capacity

At the outset of this chapter, no specific individual system builder was identified. It has not been possible to distinguish specific actors, or a smaller group of actors, as system builders throughout the episodes. Instead, it has been a network of actors consisting of VTT, the universities, and the capital goods manufacturers and their customers in the pulp and paper industry that—with the support of the Ministry of Trade and Industry—has collectively strengthened the TIS of biomass gasification. This network of actors has developed various types of capital goods throughout its common history in order to increase the competitiveness of the pulp and paper industry, and to reduce their dependency on energy imports. More recently, two distinct alliances have been formed for realising the production of second-generation fuels based on biomass gasification.

For the various actors within the network, extending the design space of fluidised bed combustion to include fluidised bed gasification has not represented a significant break with established values or practices. Instead, the TIS of fluidised bed biomass gasification has been largely embedded in the TIS of fluidised bed combustion in Finland, and the need for a specific actor to take on the role of the system builder has, therefore, been limited. This also means that internal resources of the TIS were available for experimenting with gasification. The Finnish actors, therefore, have had to rely on the general structure beyond this network to a much lesser extent than the system builders in the other countries.

Since 1973, the field of biomass gasification has progressed tremendously. Rather than attributing this progress to the achievements of a single system builder or an alliance, it has been made possible by contributions from various actors in the network. I will now briefly comment on the contributions made by VTT, the universities, the capital goods industry and their customers, as well as the Ministry of Industry and Technology in developing the field.

VTT has, since the beginning of the 1970s, been learning from and contributing to almost all major gasification projects in Finland, as well as two major projects in Sweden. Even if some of the large-scale experiments may be judged as failed attempts to commercialise the technology, VTT has been able to learn important lessons from these failures.

Through VTT's experiments and by focusing its research on process development, VTT has been able to construct a world-class science and technology infrastructure for experimenting with biomass gasification for a wide range of applications. In addition, with the continuous interest in the CHP application and support from the government through a mixture of research and development grants, the level of knowledge has been maintained and developed even when interest in the technology has been relatively low in industry. Hence, when interest in the technology picked up again in 2003, VTT was able to respond quickly by setting up a research project with relevant actors and illustrate how and where the technology could best be configured and integrated, given the existing industry structure in Finland. It may, therefore, be argued that VTT contributes to system dynamics by acting as an important "node" and "system memory" in the Finnish network, attracting actors and facilitating the formation of the two more recent alliances. VTT, thus, strengthen the technology, network and actor structure in the TIS, in addition to the functions of *knowledge development*, *entrepreneurial experimentation* and *materialisation,* as well as *direction of search* and *legitimisation.*

The contributions to system dynamics of the academic sector, in relation to VTT, have been equally important. One could argue that the strong position of VTT cannibalises the academic sector, making it more difficult for universities to compete for research grants and industry contracts, at least in the field of biomass gasification. Such a scenario has played out in the case of some of the weaker research groups (Fogelholm, 2008), but it has also been argued that strong competition with VTT has forced universities to focus more on the basic science of the field and not on process development or other areas where VTT is relatively strong (Hupa, 2008). Through collaboration with industry and VTT, some of the stronger academic departments have been able to excel and benefit from the collaborations, becoming even stronger in basic science and strengthening, mostly, the function of *resource mobilisation*, *knowledge development and diffusion.* Furthermore, it has been argued that the collaboration and division of labour between the actors has resulted in an arrangement where the researchers could focus on research, while the industry partners could focus on commercialising the results (Hupa, 2008).

The contributions to system dynamics of the capital goods industry has taken the form of an active participant in collaboration with their customers for testing and implementing new products and processes. Through their active participation in the research programmes Liekkie and Jalo, their "absorptive capacity" (Cohen and Levinthal, 1990) was strengthened. This enabled them to appropriate on the knowledge development in terms of identifying potential patents, business opportunities and new product areas. The capital goods industry and their customers have strengthened *resource mobilisation, knowledge development, entrepreneurial experimentation, materialisation,* and *market formation* for less advanced applications of the TIS. In addition, they are most likely a dominant force in setting the agenda in terms of *direction of search* and *legitimation* of the technology, feed-stocks, and applications to experiment with. Hence, Finnish industry has not moved beyond the design space of the fluidised bed technology and experimented with, for example, entrained-flow and black liquor gasification.

Finally, the Ministry of Trade and Industry has played a key role in designing a long-term industrial policy that has considerably strengthened the existing actor network. Finland decided early not to devote any significant resources to nuclear power research and instead focus on developing domestic peat and biomass resources for energy purposes, based on the development of new technologies and methods. The core of this strategy was the launch of 10 research programmes during the mid-1980s. Through the various programmes the function of *resource mobilisation* was considerably strengthened and the level of knowledge increased considerably (*knowledge development and diffusion*). As a result, Finland became an attractive location for multinational corporations to focus their research and development activities.

The collective transformative capacity of the network of actors has been able to strengthen all of the functions of the TIS, except for *market formation* for the more advanced applications of BIGCC and renewable transportation fuels and other chemicals. It has also strengthened the structure of the TIS, as experience has accumulated from one episode to another and the actors have been able to build larger and larger plants, use more difficult feed-stocks, and test more advanced applications. The network has, thus, strengthened the technology structure with various pilot plants, demonstration plants and commercial-scale plants, as well as with the creation of an advanced science and technology infrastructure for enabling further experiments and knowledge development. The organisational structure has also been strengthened with new gasification specialist firms such as Carbona, but most importantly by strengthening the position of the incumbent capital goods industry, VTT and universities in the field.

The limits of their transformative capacity as the well as the potential system weaknesses will now be identified and discussed, as will the potential role of policy in addressing these weaknesses.

8.5.2 Limits of the system builders' transformative capacity, system weaknesses and the potential role of policy

Athough the Finnish network of actors has created a strong structure and strengthened all of the functions of the TIS, there are still limits to what it has been able to accomplish. By explaining these limits, it is possible to identify a set of system weaknesses that must be addressed by policymakers and system builders for realising biomass gasification for more advanced applications, such as the production of second-generation fuels.

To begin with, it was not until 2003 that the *direction of search* shifted towards the development of renewable transportation fuels in Finland. Prior to that, the actors in the TIS paid very little attention to developing gasification for fuel and chemical synthesis, even during the first episode.

For succeeding in the production of second-generation fuels, it is necessary to extend the design space beyond the TIS of combustion, and the existing synthesis process will have to be more or less modified (when using fludised bed gasification, see Chapter III). However, although the Finnish actors have extensive experience with gasification, they have very little experience making an ultra-clean gas suitable for various synthesis processes. The exception was the Oulu ammonia plant during the end of the 1980s. VTT participated in the development work, but it was the German engineering firm Uhde that supplied the gasification and enabled the integration with synthesis technology.

As mentioned above, the Finnish actors have not extended the design space of biomass gasification beyond that of combustion to also include chemical synthesis. Even if there are plenty of potential suppliers of various types of catalysts, they are currently not taking part in the technology development undertaken by the two main alliances.[274] The Finnish actors rather see the synthesis technology as “off-the-shelf” technology that can be acquired once the large-scale plants are built.

There may, of course, be a range of opinions with regard to the extent of adaptation necessary and whether the synthesis technology is an “off-the-shelf” technology when applied to biomass gasification. However, what makes it particularly problematic is that the two alliances focus on FT diesel production.

The production of FT-liquids is a far more advanced and less well-known synthesis technology than methanol or DME. In total, there are only four operating plants in the world and two proprietary owners of the technology with commercial experience, Shell and Sasol (GASIF, 2007). Sasol operates three of the plants based on coal gasification and Shell has one plant in operation in Malaysia based on natural gas. Hence, FT synthesis has never been used on a commercial-scale in combination with low temperature gasification or biomass. More recently, Shell has attempted to combine the synthesis process with high temperature gasification of biomass in Germany (Choren), but withdrew from the project (see Chapter VI).

It may, therefore, be very difficult for the Finnish actors to extend their alliances to include Shell or Sasol. Those companies appear to have little interest in biomass gasification but are engaged in several projects based on coal gasification and reforming natural gas, for which the technology has already been demonstrated. Hence,

The first system weakness is the lack of technology structure due to a lack of actors from complementary knowledge fields taking part in catalyst development and in the adaption of the downstream synthesis processes.

An option, of course, is to collaborate with a new supplier of catalysts for FT diesel. Since the new actors have no reference plants, the Finnish alliances cannot, however, argue that it is an off-the-shelf technology. Before deciding to construct the first commercial-scale plant,

[274] Not officially at least.

the technology needs to be successfully demonstrated, at least on the scale of the current demonstration plants.

The risk involved for the commercial actors is that the first demonstration phase will take considerably longer and be considerably more expensive than anticipated. The system builders can address this system weakness by switching to a synthesis process with which there is more experience. The role of policy would be to provide “patient capital”, i.e. financing research and development at the demonstration facilities on different and suitable catalyst processes in collaboration with potential suppliers, thereby extending the alliances to also include catalyst developers.

There is also a second system weakness. The actors have been successful in developing different technical solutions for various applications for biomass gasification, including on a commercial-scale. However, innovative but immature technologies such as BIGCC for electricity production have not been supported beyond investment subsidies in the range of 10-20 percent and have not, therefore, had the chance to become competitive with conventional alternatives. Throughout the history of biomass gasification, the network of actors has not attempted to align the institutional framework, creating niche markets for immature technology and thereby support their development.

It was previously argued that the pulp and paper industry dominates political life in Finland (Donner-Amnell, 2000). Just as in the case of Sweden, the pulp and paper industry has a limited interest in promoting new technologies that would increase the price of their main feed-stocks, biomass and electricity. Any special provisions for emerging biomass-based technologies that would increase the price of biomass and electricity would, therefore, not be expected to be supported by the industry (and, for that matter, have not been suggested). For instance, even if a CO_2 tax was introduced and gradually increased, a number of exceptions to the law were implemented to avoid imposing additional costs on the industry (Vehmas et al., 1999; Vehmas, 2005). The network of actors, therefore, appears to be limited in its capacity to strengthen *market formation* through aligning the institutional framework to create niche markets for emerging technologies. Hence, *The second system weakness is the lack of an institutional framework that recognises the need for creating specific market preconditions in support of emerging technologies.*

The government has chosen not to take the lead in environmental protection or abating climate change in ways that could lead to higher costs for the dominant pulp and paper industry (MTI, 2005; Hildén, 2008). Finland has chosen to support the use of peat and biomass for oil substitution with the intention of increasing the competitiveness of both the capital goods industry and pulp and paper industry. As a result, the use of biomass for electricity production in Finland is the highest in Europe (Eurostat, 2009).[275] However, other forms of renewable energy have not been identified as strategically important and have received little support. As a result, wind and solar power have experienced relatively slow growth and has a low share of the total electricity production in comparison with the EU average.[276]

More recently, however, the government has increased its ambitions to actually reach the prescribed EU targets and form markets. For example, the Ministry of Employment and the Economy (formerly MTI) has suggested that Finland should adopt a feed-in law to promote wind power. The new goal has been set to increase production from 0.2TWh to 6TWh and thereby cover 24 percent of Finland's obligations by the year 2020 (MEE, 2009). With regard to renewable transportation fuels, the Ministry has indicated an increased level of ambition. In June 2009, during the inauguration of the Varkaus demonstration plant, the Minister of Employment and Economics, Mauri Pekkarinen, announced that Finland would exceed EU biofuel Directive 2009/28/EC, proposing a target of 10 percent by as early as 2015 and 15-20 percent by 2020 (Saarinen, 2009). The new targets and additional incentive structures to reach these targets have not yet been adopted in parliament.

In combination with the new targets, the Ministry has estimated that the government needs to support the proposed projects with investment subsidies in the range of €100 million per

[275] In 2008, 13 percent of the gross electricity produced in Finland was generated in biomass-fired power stations. That is the highest figure in the entire EU, which averaged 3.2 percent (Eurostat, 2009).

[276] In 2008, 0.34 percent of the gross electricity production in Finland came from wind power, compared with the EU average of 3.52 percent (Eurostat, 2009). Finland produced 2.48 percent of all gross electricity among the EU15, but their share of the total production of electricity from solar and wind was 0.21 and 0.24 percent, respectively. In absolute numbers Finland produced 170GWh of wind and 3GWh of solar during that same year (Eurostat, 2009).

full-scale plant (approximately 25 percent of the total investment cost) or about €200 million in total by 2010–2011.[277] It remains to be seen if these incentives will be sufficient to induce investments.

8.6 Conclusions

Broadly, the same network of actors—responsible for developing and using advanced and innovative paper machines, as well as fluidised bed combustion technology—has taken on the system building role with regard to fluidised bed gasification. In three main episodes, since 1973, this network of actors has conducted various experiments with different type of feed-stocks and for a wide range of more and less advanced applications.

In the first episode, the oil crisis provided incentives for the actors to start experimenting with technologies for oil substitution in the pulp and paper industry. Gasification of biomass for the lime kilns was developed and found a commercial application as long as the price of oil was high. During the second episode, there was a demand for increasing electrical efficiency by a better utilisation of the existing heat sinks since nuclear power became politically impossible to pursue. Based on experience from the previous episode, the capital goods industry was able to respond by developing pressurised solutions for biomass gasification, as well as less advanced gasification technologies for electricity production. In the third episode, the interest shifted towards the production of renewable fuels from gasification and almost the same network of actors was able to mobilise the necessary resources to set up two competing alliances for commercialising an opportunity based on previous experiences.

In Finland, it is not a particular system builder or formal alliance that the creation of the TIS can be attributed to, but rather an established network of actors that has experimented with the design space of fluidised combustion to also include that of biomass gasification. Instead of emphasising the particular role of a single system builder, different contributions to system dynamics and interplay between the various actors in the network were highlighted.

[277] This is not to say that each project will be supported by funding or with how much. Currently, no decisions have yet been made (Saarinen, 2009).

VTT has an important role as the node and "collective memory" of the system. Since the first episode, it has been involved in nearly all major gasification projects in Finland, as well as in two major ones involving BIGCC in Sweden (see Chapter VII). VTT has been able to learn from all of the projects and draw important lessons for following projects. Over time, it has constructed a world leading science and technology infrastructure for fluidised bed gasification.

The universities appear to have been able to advance their position in basic science, since VTT has been focused on research on process development. Since the mid-1980s, industry has participated in major joint research programmes with VTT and the universities. These collaborations have created a division of labour where the researchers could focus on research and industry could focus on process development and finding commercial applications of the research. The role of the Ministry of Trade and Industry was emphasised as important for making the programmes possible in the first place and for recognising early on the strategic importance of the capital goods industry.

Due to these programmes, and in combination with the various large-scale experiments, the level of knowledge and number of experts active in the field were significantly enhanced. As a result, the entire actor and technology structure could be strengthened, which made Finland attractive to major multinationals in the field. Collectively, the network of actors has been able to strengthen the structure of the TIS and all of the functions, except for *market formation* for BIGCC and the production of renewable fuels.

Although the Finnish system appears to be strong, two main system weaknesses can be identified based on the limits of the transformative capacity of the network. First, it was concluded that actors had been limited in their capacity to extend the design space of biomass gasification beyond the design space of combustion to also include chemical synthesis. Throughout the history of biomass gasification, the network has had only one experiment with chemical synthesis—at the ammonia plant in Oulu in the late-1980s. Since then, the focus has not been on developing the catalyst competencies, and the current alliances have communicated that it is an "off-the-shelf" technology that they will contract once they are ready to build the first commercial-scale demonstration plant. Throughout this thesis, however, it has been argued that combining low temperature gasification with chemical synthesis for the production of renewable fuels will require further demonstration and development work of the downstream process. Hence,

The first system weakness is the lack of technology structure due to a lack of actors from complementary knowledge fields taking part in catalyst development and in the adaption of the downstream synthesis processes.

This weakness is, of course, best addressed by including catalyst developers already at the demonstration stage. For example, since the demonstration facility at Varkaus carries its own operating costs, continuous experimentation to achieve a syngas quality could also include the development and demonstration of various catalysts for fuel and chemical synthesis. The role of the government may, of course, be to support the development with additional funding for further developing these competencies in Finland in collaboration with international actors.

The second weakness concerns the network's inability to strengthen market formation by acting to align the institutional framework to create niche markets for emerging technologies. Throughout the history of biomass gasification, the only available support for making the technology competitive with the incumbent alternatives has been relatively low levels of investment support. The need for programmes to create a market to support the technology to improve its price-performance ratio has not been recognised. Hence,

The second system weakness is the lack of an institutional framework that recognises the need for creating specific market preconditions in support of emerging technologies.

The government has been extremely careful in introducing incentives that could increase the cost of biomass and electricity to the pulp and paper industry. As result, Finland has been one of the laggards within the EU with respect to environmental and climate targets. Despite this, the head of the ministry has recently indicated that they intend to take the lead in Europe on the development of second-generation fuels. It remains to be seen though if the government will introduce measures to form markets from second-generation transportation fuels.

Part III

Back to the future

Chapter IX
Cross-country analysis

In Chapter I, the purpose of this thesis was formulated as to:

" ... analyse the role of the system builders in the emergence of an industry with the capacity to realise the potential of gasified biomass for the production of second-generation transportation fuels and other chemicals within the European Union."

In Chapter II, this purpose was broken down into four research questions, each of which was addressed in the four countries studied (Chapters V-VIII). The questions were formulated as:

1) *Who act as system builders in the different national contexts?*
2) *What characterises the nature and extent of the system builders' transformative capacity?*
    a. *How do the system builders make use of the general structure in which they are embedded to form or strengthen the structure and the various functions of the TIS?*
    b. *To which extent do the system builders manage to strengthen the structure and functions of the TIS?*
3) *What are the limits to the system builders' transformative capacity and how can these be explained?*
4) *Given these limits, which system weaknesses remain to be resolved by system builders and policymakers on different levels (national and EU)?*

On a country level, the answers to each question have been summarised in Tables 9.1-9.5, and the research questions will now be addressed through a cross-country analysis. The first two questions will be analysed separately in Section 9.1 and Section 9.2, respectively. Questions three and four will be addressed in Section 9.3, since it is convenient to specify the limits of the system builders' transformative capacity and simultaneously address the system weaknesses that are natural consequences of these limits.

9.1 RQ1: The identity of the system builders

This section provides answers to the first research question:

1) *Who act as system builders in the different national contexts?*

The relevance of the question stems from previous literature in which the entrepreneur, system builder and prime mover in a new technological field have been assigned a particularly important role for addressing various technical, organisational and institutional uncertainties (Schumpeter, 1934; Hughes, 1983; Hughes, 1987; Summerton, 1994; Carlsson and Jacobsson, 1997). The entrepreneurs and system builders have often been portrayed as extremely capable individuals, while the prime movers have been described as new technology-based firms, established firms investing into new technological fields, or as networks of actors.

In this thesis, a wide array of actors taking on the role of the system builder has been identified (see Table 9.1). In the case of Austria, the system builder was an individual—a professor in chemical engineering at the Technical University of Vienna. This individual managed to create a network of actors, which over time has taken over the system building role. In Germany, the role of the institutes as the system builder was emphasised, even though a privately owned start-up company was also found to take on that role. In Sweden, a strong network of actors such as Götaverken, ABB Fläkt and Studsvik/TPS emerged during the 1970–80s. However, when Sydkraft and Vattenfall entered the TIS in the 1990s, the main actors from the previous episode exited and the network was weakened. A partially new, but also weak, network of actors could eventually be formed in early-2000s, primarily consisting of TPS, the Swedish Energy Agency and VVBGC. In black liquor gasification, the main system builder has always been Chemrec, but Nykomb Synergetics and the Swedish Energy Agency also undertook pivotal system building activities. In particular, the actions undertaken by the Swedish Energy Agency in enabling the survival of Chemrec were highlighted. More recently, Göteborg Energy has taken on a system building role. In the Finnish case, it was an already established network of actors that carried out the system building activities by extending the design space of fluidised bed combustion to also include gasification for various applications.

Table 9.1: The system builder in the four different case studies.

Austria	An individual professor created a network of actors, which over time has taken over the system building role.
Germany	Three institutes appear to have institutionalised the system building role, even though a small privately owned start-up company was also found to take on the role.
Sweden	A diminishing network in fluidised bed gasification in which actors have entered and exited, but in which TPS has remained a central actor until it was forced into reconstruction in 2007. The Swedish Energy Agency took a major system building role in the third episode. In addition, Chemrec, Nykomb Synergetics and the Swedish Energy Agency have taken on the role of system builders in entrained flow gasification of black liquor. More recently, a municipal-owned utility has acted as system builder for the Austrian FICFB technology.
Finland	An established network of actors undertakes system building activities by experimenting with biomass gasification for various applications, extending the design space of already established technologies.

Clearly, the system building role should not be associated with a specific organisational form, but can be undertaken by a multitude of actors such as: individuals, institutes, policymakers, utilities, established networks, and private firms. The common link between all these system builders is that they act to form alliances (or networks) with actors along the value chain with the required complementary resources and competencies for commercialising the knowledge field. After having successfully created such alliances (or networks), these alliances (or networks) take over the system building role even if certain individuals can remain very influential in the networks.

9.2 RQ2: The nature and extent of the system builders' transformative capacity

The second research question was broken down into two sub-questions. In this section, the two sub-questions will first be analysed before providing an answer to the main question:

2) *What characterises the nature and extent of the system builders' transformative capacity?*
   a) *How do the system builders make use of the general structure in which they are embedded to form or strengthen the structure of the TIS and its various functions?*

b) *To which extent do the system builders manage to strengthen the structure and functions of the TIS?*

The answer to the first sub-question (RQ2a) is summarised in Table 9.2. It illustrates that the system builders make use of the general structure by drawing resources from it in three different ways.[278]

First, they utilise the existing technology structure in related fields for developing the new. Hence, depending on their personal experience and technology resources available to them, they develop different solutions to the same problem. For example, the strength of coal gasification technology in Germany has led the actors to draw upon that knowledge base, while many actors in Sweden and Finland have drawn upon the knowledge developed for fluidised bed combustion. The exception in the Nordic countries is the development of black liquor gasification in Sweden, which draws on the experience from entrained flow gasification of fossil resources (see Germany (1), Sweden (FB-1, BL-1) and Finland (1) in Table 9.2).

Second, they mobilise resources and attract actors from the existing and primarily national industry structure by aligning the technology to their interests and existing technologies. For example, in Germany the system builder Choren could draw resources from the main automotive manufacturers—Daimler and Volkswagen—by providing a solution for alternative fuels that it considered technically superior to first-generation fuels. Likewise, FZK could draw resources from the incumbent gasification capital goods industries by offering a solution suitable for its existing reactors and downstream processes used for fossil gasification (see Germany (2) in Table 9.2). In Sweden, Volvo developed an interest in DME as an alternative fuel for heavy-duty vehicles in the 1990s. This interest, in combination with the Swedish Energy Agency's interest to save Värnamo, made it possible for TPS to re-enter the TIS in Sweden and a new network of actors with an interest in developing fluidised bed gasification could be formed (see Sweden (FB-2) in Table 9.2).

[278] Examples from the table will be used for illustrating these three different ways, without repeating the entire content of Table 9.2.

Also, Chemrec was able to exploit the interests of Volvo, and other elements in the structure, to set up a strong alliance, including all actors necessary for demonstrating the entire value chain from black liquor gasification to the use of DME in heavy-duty vehicles (see Sweden (BL 2) in Table 9.2). In Finland, the actors have been able to mobilise resources by attracting/aligning the technology to the interests of actors within the already established network for developing fluidised bed combustion, including the pulp and paper industries (see Finland (2) in Table 9.2).

Third, resources are mobilised in conjunction with crises (oil, financial, nuclear, climate, and other industry-specific crises), using development support available for underdeveloped regions, exploiting agricultural- and forestry-based interests in finding additional revenues, as well as drawing on both technology-neutral and technology-specific instruments. For example, in Austria resources could be attracted since Güssing could apply for regional development support. In addition, the existence of the EEG law made it possible to explore CHP gasification, which in turn enabled the system builders to start experimenting with more advanced applications (see Austria (3) in Table 9.2). Similarly, due to oil, nuclear and climate crises in Finland and Sweden, funds were made available to the system builders, which enabled them to start experimenting with various applications (see Finland (3) and Sweden (BL and FB 3) in Table 9.2).

In three out of four cases, the system builders have made use of the structure in which they are embedded to create elements of a new structure specific for biomass gasification. In the Finnish case, however, it has rather been a matter of a number of individuals being able to draw upon internal resources of the TIS for fluidised bed combustion, thereby extending the design space to include various applications of biomass gasification.

In conclusion, the respective TIS are shaped through the interaction between the system builders and their primarily local context (general structure). This interaction requires that the technological trajectories pursued must be aligned with the general industrial and institutional structure in which they are embedded.

This highlights the path dependency of the process in which new TIS are formed, drawing on related industries (Porter, 1990a). Therefore, the extent of the system builders' transformative capacity is conditioned, although not determined, by the general structure in which they are embedded. I will now proceed to analyse the extent of the system builders' transformative capacity (RQ2b), first with respect to the functions and then to the structure of the TIS.

Table 9.2: How the system builders make use of the general structure to strengthen the TIS

Austria	(1) Utilising the existing technology structure by drawing upon coal gasification and combining it with knowledge of biomass for creating small-scale systems. (2) Mobilising resources by attracting a) incumbent capital goods manufacturer AEE through personal contacts to explore the small-scale CHP application, and b) international collaborations to develop the technology by offering a research platform. (3) Mobilising resources available due to a) the town of Güssing situated in an underdeveloped region and with an interest in becoming independent on imported resources, b) EU and Austrian regional development funds, and c) the EEG and a risk absorption scheme.
Germany	(1) Utilising the existing technology structure by drawing upon fossil gasification and existing fossil-based technologies. (2) Mobilising resources by attracting/aligning the technology to the interests of a) the automobile manufacturers, and b) the incumbent gasification capital goods industries. (3) Mobilising resources from a wide range of technology-neutral and technology-specific instruments to solve climate, job and nuclear crises, as well as for supporting agricultural interests.
Sweden – Black Liquor (BL)	(1) Utilising the existing technology structure by drawing upon a) fossil gasification and technology developed in Nynäshamn for producing methanol, and b) ceramic technology developed for space shuttles in the US. (2) Mobilising resources by attracting/aligning the technology to the interests of a) the pulp and paper industry for boosting capacity in existing recovery boilers and finding additional revenues, and b) Volvo and other actors' interest in DME. (3) Mobilising resources available due to a) nuclear crises and b) climate crises.
Sweden – Fluidised Bed (FB)	(1) Utilising the existing technology structure by drawing upon fluidised bed combustion. (2) Mobilising resources by attracting/aligning the technology to the interests of a) municipal utilities in Sweden and Europe interested in a medium-scale solution, b) Volvo's interest in DME, and c) the Swedish Energy Agency's interest in saving Värnamo. (3) Mobilising resources available due to a) oil crises and b) climate crises—Shell, World Bank, EU.
Finland	(1) Utilising the existing technology structure by drawing upon fluidised bed gasification. (2) Mobilising resources by attracting/aligning the technology to the interests of a) actors within an already established network for developing fluidised bed combustion, and b) the pulp and paper industries for finding additional revenues. (3) Mobilising resources available due to a) oil and nuclear crises, b) MTI long-term and strategic industry support, and c) climate and forestry crises.

When all the functions in a TIS are strengthened, a “system building motor” is formed (Suurs, 2009). In this particular case, the virtuous circles created in the motor, feed and receive feed-back from the three structural elements in Figure 9.1.[279]

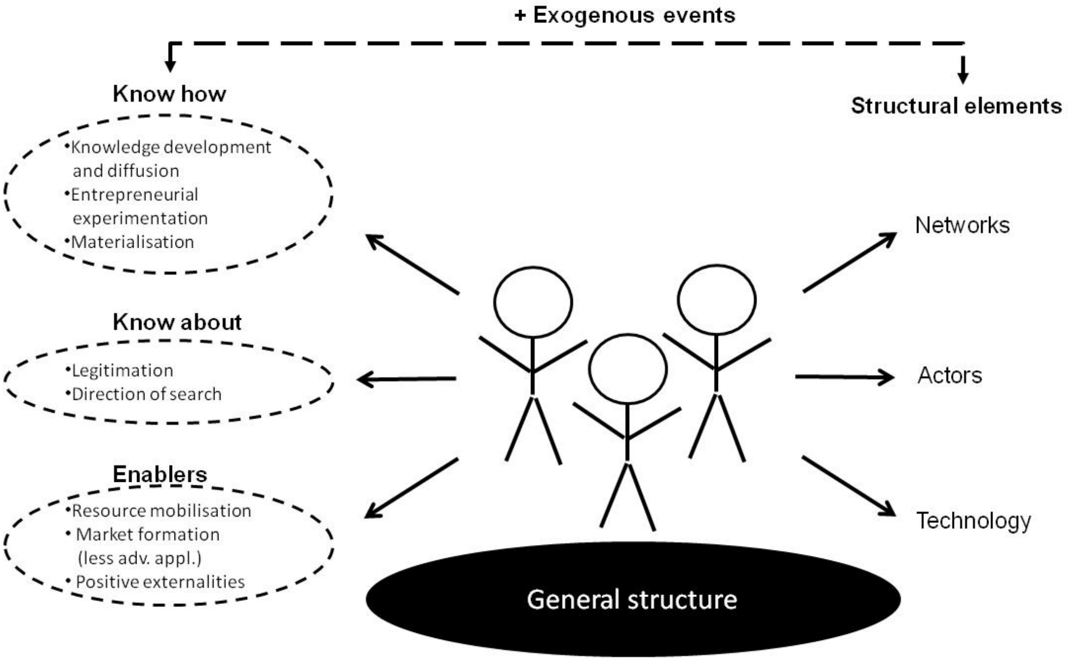

Figure 9.1: The system builders’ impact on functions and structure.

The functions involved in the system building motor can be divided into three sets of epistemologically different functions (see Table 2.3 in Chapter II and Figure 9.1). The first set of functions—*knowledge development and diffusion*, *entrepreneurial experimentation* and *materialisation*—is strengthened by the system builders when they build pilot-, demonstration- and commercial-scale plants; conduct basic and experimental research at these plants; test various types of feed-stocks; and experiment with different applications. It was argued in Chapter II that this particular set of functions strengthens the system builders' know-how in plant construction. A strong motor that includes the “know how” functions is necessary for strengthening the capacity of the system builders in moving from pilot to demonstration plants, and from demonstration plants to the first commercial-scale plants, as well as for improving the competitiveness of such plants in the long run (learning curve).

[279] The exact inter-functional and functional-structural dynamics involved will not be the focus of the analysis.

In a similar manner, the second set of functions can be referred to as "know about" functions, including the functions of *direction of search* and *legitimation*. The system builder has strengthened them, for example, by conducting system studies and informing about the benefits of the production of second-generation fuels over other alternatives, by aligning the technology to the interest of actors and elements in the general structure in which they are embedded, and by being able to show pilot-, demonstration-, and commercial-scale plants in operation. Legitimation and direction of search are, of course, also strengthened by exogenous events such as crises (oil, nuclear, climate), as well as increased public awareness of, for example, the negative externalities associated with the use of coal.

Such exogenous factors may also strengthen the third set of functions, here called "enablers", including the functions of *resource mobilisation, market formation* and the generation of *positive externalities.* However, in this thesis it has been illustrated that the system builders have also, skilfully and to a great extent, been able to strengthen these enablers.[280] To begin with and as already argued in connection with RQ2a, *resource mobilisation* has been strengthened by the system builders as they use the general structure in which they are embedded to draw resources. This structure includes, for instance, the agriculture and forestry industries, incumbent capital goods suppliers, governmental research, and development funds (See 1-3 in Table 9.2).

With these resources, they have strengthened the "know how" functions by conducting *entrepreneurial experiments* and engaging in *knowledge development,* which has enabled them to materialise (*materialisation*) new types of plants and designs (resulting in a stronger technology structure of the TIS). In addition, with these resources they have been able to strengthen the "know about" functions—*direction of search* and *legitimation*—as pilot and demonstration plants that are taken into operation can be used to attract investors and other actors to the TIS.

The second enabling function—*market formation*—is strengthened by the ingenuity of the system builder in experimenting with the technology and adapting it to an existing or, by

[280] Exogenous factors have previously been emphasised as being dominant in the formative phase, and it has been argued that the actors' ability to strengthen the key innovation and diffusion processes are limited in the early phase (Raven, 2005; Bergek et al., 2008a).

exogenous events, changing general structure and changes in relative prices. In the case of biomass gasification, these factors have enabled the system builders to explore and commercialise less advanced applications and, thereby, find a commercial use of the technology for oil substitution in lime kilns, boosting the capacity of conventional recovery boilers, advanced recycling of paper waste, co-firing with coal, and combined heat and power generation with gas engines (see Chapters III and VII-VIII). However, so far the system builders have not strengthened market formation by explicitly acting to align the institutional framework to the technology.

By strengthening *market formation*, the system builders engage in the extremely important interaction with the first paying customers—"lead users" (Von Hippel, 1986). The "know how" functions can thereby be strengthened as such customers provide information and feedback on possible improvements.[281] In addition, the "know about" functions can be strengthened as the system builders gain access to reference installations, if operated successfully (cf. Falkus (1982)).

As a result of the activities of the system builders and as the TIS progresses, *positive externalities* arise. These often benefit more recent entrants, enabling them to mobilise resources and identify new opportunities based on achievements and lessons made by earlier entrants. For example, it was illustrated that the experiments undertaken by system builders in Austria created a science and technology infrastructure that made it possible for a German alliance, headed by ZSW, to identify new opportunities and rapidly catch up with the technology development, and for an alliance in Sweden to construct a new type of FICFB gasification plant that may be used for retrofitting existing CFB combustion plants (see Chapters VI-VII). The development of *positive externalities* may thus strengthen both the "know about" and "know how" functions.

The system builders have been able to create an embryonic *structure* of the TIS by strengthening it directly or through the three sets of functions discussed above. In the process, they have been particularly successful in creating and strengthening the structural

[281] See, for example, the importance of the Booster plant in New Bern, USA for Chemrec in Chapter VII.

elements of knowledge networks, actors and technology. In turn, these add to the dynamics of the TIS by further strengthening the three sets of functions (see Figure 9.1 and Table 9.3).

To begin with, all system builders have created or taken part in knowledge networks (see Table 9.3). From these, they have been able to draw substantial resources. For example, Chemrec and the Swedish Energy Agency created the BLG Programme through which Chemrec could access substantial resources, enabling the construction of the pilot plant i Piteå (see Chemrec in Table 9.3). Choren and Volkswagen set up the network RENEW through which substantial resources were mobilised (see Germany in Table 9.3).

These networks not only strengthen the enabling functions *resource mobilisation* and *development of positive externalities,* but also the "know about" and "know how" functions. As mentioned previously, the "know about" functions of the emerging TIS were strengthened, as the networks engaged in conducting system studies and informing about the benefits of the production of second-generation fuels over other alternatives, etc. The "know how" function is strengthened, as strong networks enable the system builder to conduct more advanced experiments, wherein ideas and resources can be generated for materialising new design alternatives, etc.

By aligning the technology to the interests of the current industry structure (influencing *direction of search* and *legitimation*), the system builders have attracted a heterogeneous mixture of private and public organisations to the TIS. Such actors bring resources, competencies and experience. With more resources, the construction of further demonstration- and commercial-scale plants are enabled, and feed-stocks and various types of applications can be experimented with.

For example, FZK strengthened the "know how" functions when experimenting with the production and gasification of pyrolysis oil from straw in the existing pilot facilities of Future Energy (Siemens) (see Chapter VI). By illustrating that its technology had the potential to produce large volumes of second-generation fuels using the gasification and downstream equipment for fossil gasification, it strengthened the "know about" functions. As a result, it was able to create an alliance with Lurgi and other firms along the entire value chain for demonstrating the concept of the technology on a larger scale, which in turn strengthened the "know about" functions, inducing more entrants into the TIS. Indeed, all system builders act to strengthen the "know how" and "know about" functions to form alliances, strengthening the structural elements of actors and networks of the TIS (see Table 9.3). The system builders can also create spin-off companies and new firms directly, as in the case of Choren and Repotec.

By attracting actors and forming networks, the system builders strengthen the structural element of technology. In the field of biomass gasification, new knowledge is developed, tested and experimented with by building pilot and demonstration plants that become a central part of the science and technology infrastructure of the field.[282] The development of such an infrastructure is necessary for strengthening the "know how" functions, thereby accumulating knowledge and advancing the field towards large-scale production of second-generation fuels based on various types of feed-stocks. As already mentioned, an advanced science and technology infrastructure is also important for strengthening the "know about" and enabling functions of the TIS, since an advanced technology structure attracts actors and can become central to the formation of new knowledge networks, for example Güssing. All system builders, therefore, construct pilot-, demonstration- and commercial-scale plants for various applications and feed-stocks (see Table 9.3). The specific contributions of pilot and demonstration plants to system dynamics will be elaborated on in Chapter X.

In sum, in terms of the extent of the system builders' transformative capacity (RQ2b), the system builders have been capable of strengthening the three sets of functions "know about", "know how" and "enablers", as well as the three structural elements knowledge networks, actors and technology. By strengthening these functions and structure, the system builders set in motion cumulative and virtuous circles between the functions, as well as between the functions and the structural elements that progresses the TIS within the formative phase.

With respect to the complete research question two (RQ2), it is concluded that the nature and extent of the transformative capacity of the system builders is conditioned, although not determined, by the general structure in which they are embedded and from which they

[282] Sometimes, these plants have become central in the formation of new knowledge networks.

manage to strengthen the enabling functions. With these enablers, they have been successful in strengthening the "know how" and "know about" functions, as well as structural elements of knowledge networks, actors and technology.

Table 9.3: The system builders' capacity to build structure and strengthen the various functions of the TIS.

Austria	Build Structure: building pilot and demonstration plants, and enabling second commercial CHP plant (technology); setting-up RENET and various EU knowledge networks; and attracting actors. Strengthen Functions: *knowledge development, entrepreneurial experimentation, materialisation, market formation* (CHP), *legitimation, direction of search,* and *development of positive externalities.*
Germany	Build Structure: building pilot and demonstration plants (technology); creating knowledge networks, attracting actors, and creating alliances with incumbents (actors and networks). Strengthen Functions: *resource mobilisation, knowledge development, entrepreneurial experimentation, materialisation, legitimation, direction of search,* and *development of positive externalities.*
Sweden – Black Liquor (BL)	Build Structure: building pilot-, demonstration- and commercial-scale plants for less advanced applications (technology); creating national and international knowledge networks; and attracting actors, creating alliances with incumbents (actors and networks). Strengthen Functions: *resource mobilisation, knowledge development, entrepreneurial experimentation, materialisation, legitimation, direction of search, development of positive externalities*, and *market formation* for less advanced applications.
Sweden – Fluidised Bed (FB)	Build Structure: building pilot-, demonstration- and commercial-scale plants for less advanced applications (technology); creating a knowledge network (CHRISGAS); and setting-up new organisations (VVBGC) (actors). Strengthen Functions: *knowledge development, entrepreneurial experimentation*, *materialisation,* and *market formation* for less advanced applications.
Finland	Build Structure: building pilot-, demonstration- and commercial-scale plants for less advanced applications (technology); and undertaking experiments within established network, setting up research and development programmes, and creating alliances between established actors (networks). Strengthen Functions: *resource mobilisation, knowledge development, entrepreneurial experimentation, materialisation*, *legitimation, direction of search, development of positive externalities*, and *market formation* for less advanced applications.

Largely as a result of the actions undertaken by the system builders, a system building motor of positive interconnections has emerged, resulting in a structural and functional build-up. As mentioned above, a similar type of motor has in previous literature been called a "system building" motor, and it is one of several other typical motors of the formative phase (Suurs, 2009). However, for finalising the formative phase and shifting the TIS to a phase marked with rapid market growth, the system building motor must be turned into a "market motor" in which the institutional framework is aligned to the technology (Suurs, 2009).[283] In this case, this shift implies an institutional change that results in the formation of markets for advanced applications. So far, such markets are missing.

In the next section, the limits of the system builders and remaining system weaknesses of the TIS will be analysed. These are weaknesses that must be adequately addressed if a market motor is to be set in motion.

9.3 RQ3 and RQ4: The limits to the system builders' transformative capacity and remaining system weaknesses

In this section, the focus of the analysis shifts to identifying and explaining the limits of the system builders' transformative capacity. Based on these limits, the remaining system weaknesses at the EU level will be identified. Hence, research questions three and four will be addressed:

3) *What are the limits to the system builders' transformative capacity and how can these limits be explained?*
4) *Given these limits, which system weaknesses remain to be resolved by system builders and policymakers on different levels (national and EU)?*

Throughout the case study countries, a set of 11 instances have been identified where the system builders have been limited in their capacity to strengthen one or more functions, or to create certain structural elements, which in turn has resulted in specific weaknesses of the system (see Tables 9.4 and 9.5).[284] Some of these are probably of such nature that eventually the system builders will be able to overcome them by themselves, while others will require an increased involvement of policymakers.

[283] The shift has also been conceptualised as a consequence of the occurrence of various stabilisation mechanisms (Nygaard, 2008).

[284] These tables will be referred to throughout the remaining parts of this chapter. When certain points are made, the content of the tables will be used for making illustrative examples but without repeating the entire contents for all countries.

Since the innovation process is highly contextual in nature (cf. Rosenberg (1976)), these limits and associated system weaknesses are, as clearly visible in the case studies, highly contextual as well. However, based on the context-specific interactions between the system builders and the structure in which they are embedded, it will be argued that two main and shared system weaknesses remain. The main task of policy is to address these weaknesses, thereby reducing the structural constraints of the system builders.

In spite of the strength of the system building motor, the system builders have in common a limited capacity to strengthen the "know how" functions—*knowledge development, entrepreneurial experimentation* and *materialisation*—resulting in an insufficiently strong technology and actor structure. A direct consequence of this system weakness is that current demonstration plants are not in operation and there is no production of second-generation fuels.

The first system weakness can, however, only be fully understood in relation to a second system weakness. This weakness is constituted by incomplete and weak political networks that have yet not aligned the institutional framework, thereby strengthening the system enabling function *market formation.*

Without a strong *market formation* the "know about" functions—*legitimation* and *direction of search*—will remain insufficiently strong to attract further actors with complementary competencies and resources. These are, in turn, necessary for addressing the first system weakness in terms of a weak and incomplete actor and technology structure.

The limits in the system builders' transformative capacity have, thus, created weak inter-connections between the functions and the structure, constituting the "weak motor" of the TIS (see Figure 9.2). Completing the formative phase and shifting the TIS into a growth phase involves addressing this weak motor by dealing with these two main system weaknesses.

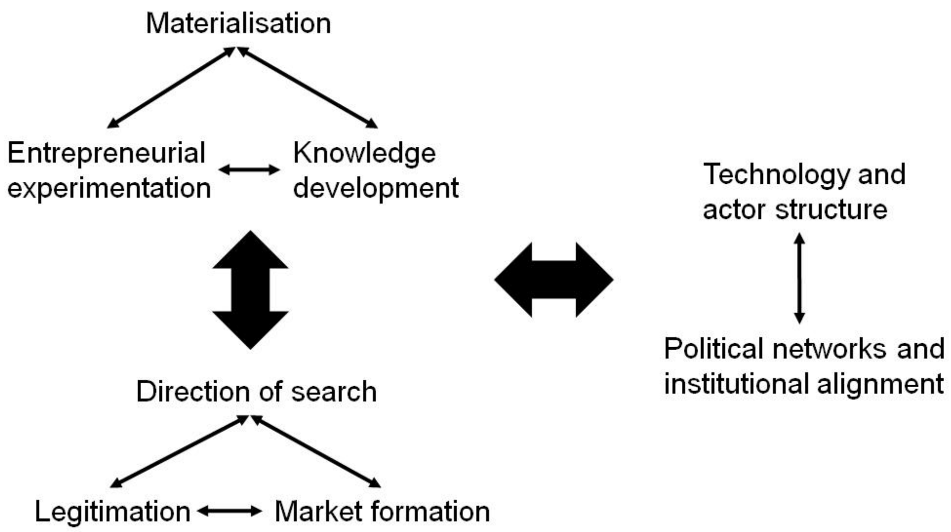

Figure 9.2: Insufficiently strong interconnection and elements from shifting the TIS into a growth phase.

In the next two subsections, the details of the two system weaknesses will be given, beginning with Austria.

9.3.1 Weakness in technology and actor structure

The recent back-lash against the support for new renewables in Austria is quite unique and has strongly influenced the possibilities to commercialise the technology in the country (see Austria (1) in Table 9.4. The system builders have been limited in their capacity to strengthen *direction of search*, *legitimation* and *market formation*, due to the unfavourable changes in the feed-in law and lack of influential actors in the network. As a result, the actor structure is weak (while the technology structure is relatively strong), and there are clear problems with regard to appropriating on the knowledge developed at the Güssing facility.

In the case of Germany, its long history of coal gasification in combination with a) the existence of an incumbent industry with extensive experience in the field, and b) a "thick" incentive structure of technology-specific, as well as technology-neutral instruments in support of renewable energy technologies, is quite unique. These combined factors have created opportunities for the system builders to draw upon a common knowledge base, strengthen the enabling functions (except for *market formation*), and form alliances consisting of firms with complementary competencies and resources along the entire value chain. However, as a result of their relatively short history in biomass gasification, the actors have accumulated limited experience from experimenting with less advanced applications for biomass gasification.[285]

Hence, even if operating from a good position, the system builders have so far been limited in their capacity to strengthen the "know how" functions enough to make the technology operational on the scale of the demonstration plants. Consequently, a main system weakness that must be addressed is the incomplete technology structure and lack of know-how for constructing functioning demonstration plants (see Germany (1) in Table 9.4).[286] Since there is no production of second-generation fuels elsewhere, the system weakness is not unique to Germany. For different reasons, it is shared between all case study countries.

In contrast to Germany, the Swedish TIS has a long history of biomass and black liquor gasification. In particular, Studsvik developed a unique competence in the field of pressurised fluidised bed gasification already in the early-1980s, well before actors in the other cases. However, instead of building upon the previous knowledge base, the two major utilities Vattenfall and Sydkraft decided to co-operate with Finnish actors. As a result, they strengthened the actor and technology structure in Finland instead of the one already developed in Sweden.

Over time, the capital goods sector in Sweden, which could supported fluidised bed gasification, has deteriorated.[287] The possibility to create commercial opportunities based on fluidised bed gasification and Swedish actor interests is, therefore, currently remote.

In Sweden, current and future actors in the field of fluidised bed gasification will be limited in their capacity to strengthen the functions of the TIS by creating alliances with national capital goods suppliers in possession of the complementary resources necessary for commercialising the technology. The main system weakness in Sweden is, thus, a lack of a capital goods industry with the capacity of entering into alliances, appropriating on knowledge development, and constructing large-scale plants (see Sweden (1) in Table 9.5).

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[285] However, as mentioned previously, they have accumulated extensive experience in fossil gasification.
[286] With time and continued support from policy, the system builders should be in a good position to overcome their current lack of know-how and take the plants into operation.
[287] The intention of this thesis is not to address why the capital goods industry, capable of constructing boilers and gasifiers, has deteriorated in Sweden.

This weakness is also valid in the case of black liquor gasification in Sweden. However, through the technology- and actor-specific policies of the Swedish Energy Agency, the system builder have been able to compensate for this weakness by building international collaborations with complementary competencies and resources. Consequently, black liquor gasification has been able to continue to develop and is now in a good position to be one of the first technologies that demonstrates continuous production of second-generation fuels.

The lack of an actor structure in Sweden (and Austria) becomes even more apparent when compared with Finland. Sweden and Finland had a similar starting point in terms of actor and technology structure in the early-1970s. However, when the Ministry of Trade and Industry decided to support the development of the capital goods industry for using domestic resources for energy purposes in the mid-1980s, the technology and actor structure in Finland was strengthened in that the knowledge level of both combustion and gasification could be significantly increased. Due to the long-term government support for research, development and demonstration, the close co-operation between customers and capital goods suppliers, and an active involvement of VTT—various more and less advanced applications could be experimented with, where lessons made from one experiment benefited the following.

These experiments have taken place over four decades. So far, the network of actors has mainly experimented with extending the design space of fluidised bed combustion to include gasification for a range of energy-related applications but not for transportation fuels. Therefore, the network has been limited in its capacity to strengthen *knowledge development*, *entrepreneurial experimentation* and *materialisation* to also include catalyst development.

The main system weakness in Finland is, therefore, in the technology structure, which lacks the contribution from actors from complementary knowledge fields taking part in catalyst development and the adaption of the downstream synthesis process to fluidised bed biomass gasification for FT diesel production (see Finland (1) in Table 9.5).

Only two firms, Sasol and Shell, have commercially operating FT diesel plants. Other catalyst developers with an interest in developing FT catalysts exist, but the process would have to be developed and demonstrated on a commercial-scale in combination with fluidised bed gasification. As of yet, incumbent catalyst developers have not entered alliances with actors involved in fluidised bed gasification.[288]

Their lack of interest can partially be explained by a strong demand for their competencies in conventional fossil gasification, but also with a preference to work with the cleaner gas from entrained flow gasification. As a result, the technology and actor structure for FT synthesis remains weak within the TIS, which may become a problem for those developing the route based on fluidised bed gasification. The alternative is, of course, to look for other types of fuels than FT diesel such as the gaseous fuels DME and BioSNG. This is also what Chemrec and the actors advocating FICFB gasification have been doing.

However, due to the intentional resistance from the automotive and oil industry with respect to DME and BioSNG, the development of new heavy-duty vehicles for BioSNG has been limited, and the weak motor has resulted in a limited physical infrastructure for using BioSNG and DME (see Germany (4), Sweden (3 and 4) in Tables 9.4 and 9.5).[289] As a result, the technology and actor structure is currently weak with respect to distribution and use of gaseous second-generation fuels.

Finally, and perhaps less severely, investors in large-scale stand-alone plants (regardless of fuel) are dependent on the supply of large volumes of bioslurry, or other types of pre-treated biomass, or large areas of short rotation coppice around the plant as suggested by FZK and Choren. Such supply chains of technology and actors have not yet been formed (see Germany (3) in Table 9.4).[290] Hence, the technology and actors structure is underdeveloped upstream to these gasification processes.

In sum, although the specifics vary between the four countries, it is clear that *the first system weakness identified at the EU level is insufficient actor and technology structures in support of the development and diffusion of second-generation fuel.*

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[288] With the possible exception of Haldor Topsoe. Most recently, Haldor Topsoe appear to have entered the TIS and collaborate with Göteborg Energy on BioSNG production based on FICFB technology developed in Austria (Hedenstedt, 2010).

[289] Although Volvo has more recently started developing a diesel engine also for BioSNG (Hedenstedt, 2010).

[290] There exists a global trade of pellets, wood chips and other types of forestry residues that, to a certain extent, can compensate for this weakness.

9.3.2 Weak political networks and institutional alignment

What all of the cases study countries have in common, as in the European Union as a whole, is that none of them have adopted instruments that specifically support *market formation* for second-generation renewable transportation fuels, and few solutions have been advocated for by the nine main alliances.

This is critical since, even if the plants are made operational, the fuel produced will be considerably more expensive than both conventional liquids and first-generation fuels from sugar cane and food crops (see Chapter III). If constructed, the first demonstration- and commercial-scale plants would, therefore, have a very limited market.

For *market formation* to be strengthened, an institutional alignment must be achieved, allowing for at least initial niche markets to develop. So far, such an institutional alignment has not been possible for two principal reasons.

First, although it was previously argued that the actor structure is insufficient, the nine projects are still supported by strong alliances consisting of multinational corporations such as some of the largest automotive manufacturers in the world (Daimler, Volkswagen and Volvo); major suppliers of gasification equipment (Foster Wheeler, Andritz, Metso Power and Lurgi); world leading catalyst developers (Haldor Topsoe and Südchemie);[291] and some of the world largest pulp and paper manufacturers (UPM and Stora Enso). It would not be farfetched to suggest that these actors are also influential on the political arena. However, although the firms cooperate with a wide range of institutes, universities and start-up firms in nine specific alliances and participate in knowledge networks across the various alliances, they have so far failed to form political networks.

Through such networks, it is pivotal that a larger group of advocates agree on what they believe are reasonable "rules of the game", and argue for a common political solution in each country or for the entire European Union (cf. Van de Ven (2005)). However, instead of actors searching for common grounds, conflicts over resources and who has the "best" technical solutions dominate. Such conflicts have made the formation of political networks

[291] The catalyst developers mentioned support projects based on entrained flow gasification, save for Haldor Topsoe, who is also involved with Göteborg Energy since 2010.

and a common agenda difficult. These conflicts were illustrated in the case of Germany (see Germany (2) in Table 9.4) but are present between all system builders throughout the TIS.

Second, in the cases of Sweden and Finland, there is a lack of an institutional framework that recognises the need for creating market preconditions in support of emerging technologies (see Sweden (2) and Finland (2) in Table 9.5). Such frameworks (feed-in law) exist in Germany and Austria for renewable electricity. However, in Austria it lost in legitimacy, and after revision the incentives it provides are insufficient for CHP based on gasification to be further developed. In Sweden and Finland, technology-specific market provisions—such as the feed-in law—have never been seen as a preferred policy instrument. Instead, research and development grants and investment subsidies have been the primary tools for improving the competitiveness of emerging technologies. Although the pre-conditions were probably among the best in the world for making the BIGCC technology commercial in Finland by the end of the 1990s, these tools proved insufficient at the time for finalising the formative phase, and the technology was not made commercial (see Chapter VIII).

The second system weakness identified at the EU level is the lack of joint political network(s), advocating an alignment of institutions and technology.

Such networks are of particular importance for Sweden and Finland given the reluctance to implement technology-specific policies in support of *market formation*. Without an alignment, market formation will not be strengthened. Consequently, it will be difficult for the system builders to address the first system weaknesses by a) attracting actors with additional resources and complementary competencies for strengthening the "know how" functions, and b) developing an industrial capacity necessary for taking the existing demonstration plants in operation and mobilising enough financial capital to construct the first commercial-scale plants (cf. Chapter III).

Hence, by avoiding the question of market formation now, the system builders will have great difficulties addressing the first system weakness even with additional support from policy. Consequently, it would be difficult to finalise the formative phase by 2020 as suggested (see Table 3.4.1, Chapter III). The role of policymakers in reducing the structural constraints of the system builders, by resolving these two system weaknesses, is of pivotal importance and will be analysed in Chapter XI.

Table 9.4: The limits to the system builders' transformative capacity and system weaknesses in Austria and Germany.

	The system builder(s) have been limited in their capacity to:	***The system weakness is:***
Austria (1)	strengthen *direction of search*, *legitimation* and *market formatio*n due to a lack of influential actors in the network and associated unfavourable changes in the feed-in law.	lack of actors and political networks with an interest in aligning the institutional framework in support of the technology.
Germany (1)	strengthen *knowledge development, entrepreneurial experimentation* and *materialisation* for making the technology operational on the scale of the demonstration plants. Probably due to lack of previous experience with using biomass for less advanced applications based on entrained flow gasification.	an incomplete technology structure and lack of know-how for taking the demonstration plants into operation.
Germany (2)	strengthen *market formation* in support of the first commercial-scale demonstration plants and beyond due to fierce competition and neglecting the need for a common agenda.	the absence of joint political network(s) necessary for aligning institutions and technology.
Germany (3)	strengthen *market formation*, which in turn creates weak incentives (*direction of search*) for the creation of a supply chain for the production and distribution of bioslurry, torrefied biomass, short rotation coppice and other types of biomass necessary for large-scale production with EF gasification.	an incomplete actor and technology structure for organising a supply chain capable of handling large- scale production and distribution of biomass suitable for EF gasification.
Germany (4)	strengthen *legitimation* and *direction of search* for using BioSNG as a transportation fuel, mainly due to intentional and frictional resistance from the automotive and petrochemical industries, as well as major gas utilities.	the lack of an actor and technology structure for using BioSNG as a transport fuel.

Table 9.5: The limits to the system builders' transformative capacity and system weaknesses in Sweden and Finland.

	The system builder(s) have been limited in their capacity to:	***The system weakness is:***
Sweden (1)	strengthen most functions of the TIS in fluidised bed gasification by creating alliances with national capital goods suppliers in possession of complementary resources necessary for commercialising the technology.	the lack of capital goods industries with the capacity of entering into alliances, appropriating on knowledge development, and constructing large-scale plants.
Sweden (2)	strengthen *market formation* for more advanced applications (including BIGCC) through the creation of niche markets with the aid of policy, mainly due to a fear of high electricity prices.	the lack of an institutional framework that recognises the need for creating specific market preconditions in support of emerging technologies.
Sweden (3)	strengthen *legitimation* and *direction of search* of the use of DME in the EU due to the frictional and intentional resistance of dominant actors.	the lack of a technology infrastructure for diffusing DME as a transportation fuel in Europe.
Sweden (4)	strengthen *legitimation* and the *direction of search* for using methane as a transportation fuel due to intentional resistance of automotive manufacturers.	an incomplete technology and actor structure for using BioSNG as a transportation fuel in heavy-duty vehicles.
Finland (1)	strengthen *knowledge development*, *entrepreneurial experimentation* and *materialisation* to also include catalyst development in combination with fluidised bed gasification of biomass.	the lack of a technology structure due to a lack of actors from complementary knowledge fields taking part in catalyst development and in the adaption of the downstream synthesis processes.
Finland (2)	strengthen *market formation* for more advanced applications (including BIGCC) through the creation of niche markets with the aid of policy, mainly due to a fear of high electricity prices.	the lack of an institutional framework that recognises the need for creating specific market preconditions in support of emerging technologies.

9.4 Conclusions

In this chapter, the four research questions were addressed and the conclusions will now be summarised.

It was concluded that the system building role should not be associated with a specific organisational form. It was illustrated that a multitude of actors such as individuals, institutes, policymakers, established networks, and private firms can act as system builders. However, in common for system builders is that they form alliances (or networks) along the value chain with other actors in possession of valuable complementary competencies and other resources. With time, these alliances (or networks) take over the system building role, even if certain individuals may remain very influential in them.

One of the system builders' primary capabilities is to use the general and TIS-specific structure, in which the system builders are embedded, for strengthening the enabling functions *resource mobilisation, market formation* and *positive externalities* in a highly path-dependent process. With these enablers, the system builders have been able to strengthen the "know how" functions—*knowledge development, entrepreneurial experimentation* and *materialisation*—building an industrial capacity for less advanced applications, and constructing a science and technology infrastructure, on which experiments with also more advanced applications can be based. In addition, they have been used for strengthening the "know about" functions—*legitimation* and *direction of search*—inducing the entry of further actors, creating networks and alliances. As a result of the actions undertaken by the system builders, the structural elements knowledge networks, actors and technology have been created and strengthened.

Although the complete dynamics caused by the system builder have not been analysed in this Chapter, it is clear that the actions undertaken by the system builder have resulted in a motor of positive interconnections, resulting in a structural and functional build-up. This "system building" motor (cf. Suurs (2009)) progresses the TIS in the formative phase. However, for finalising the formative phase and shifting the TIS to a phase marked by rapid market growth, the system building motor must be turned into a "market motor" (Suurs, 2009), in which the institutional framework is aligned to the technology.

With respect to such a shift, it is concluded that the system builders have been limited in their capacity to strengthen the "know how" and "know about" functions, as well as market formation through institutional alignment. This limited transformative capacity has resulted in two main system weaknesses, where the first concern a weak and incomplete actor and technology structure.

Although, the system builders have attracted actors with complementary competencies and resources to enter the TIS, no second-generation fuels from biomass have been produced. In addition, the involvement of catalyst developers for developing or adapting synthesis processes for fluidised bed gasification is lacking; there is a weakness in the distribution and use of gaseous second-generation fuels and in the upstream supply chain for large-scale stand-alone gasification units; and a weak national actor structure exists in Sweden and Austria with a capacity to appropriate on the knowledge development. Hence,

the first system weakness identified at the EU level is insufficient actor and technology structures in support of the development and diffusion of second-generation fuels.

Addressing the first system weaknesses involves addressing the second system weakness: strengthening *market formation* by aligning the institutional framework. However, although the TIS is supported by a wide range of multinational corporations, the system builders have been limited in their capacity to form joint political networks necessary for aligning the institutional framework to the technology, thereby strengthening *market formation.*

Such networks are necessary for communicating what the system builders perceive as reasonable rules of the game that would enable *market formation*. However, conflicts over resources and who has the "best" technical solution has made it difficult to form such networks. In addition, in Sweden and Finland there is a lack of an institutional framework that recognises the need for creating market preconditions in support of emerging technologies. Hence, *the second system weakness identified at the EU level is the lack of joint political network(s), advocating an alignment of institutions and technology.*

Without an alignment, it will be difficult for the system builders to address the first system weaknesses by, a) attracting actors with complementary competencies and resources for strengthening the "know how" functions, thereby creating the industrial capacity necessary for taking the existing demonstration plants in operation, and b) mobilising the required financial capital for constructing the first commercial-scale plants, and begin exploring the potential of second-generation fuels on a large-scale.

A suggestion on the foundation of such a policy framework will be presented in Chapter XI. However, before such an analysis is undertaken, the following chapter (Chapter X) will reflect on the contributions of other actors and elements to system dynamics.

Chapter X

Contributions to system dynamics of other elements in the structure

Throughout the thesis, the role of the system builders has been emphasised for realising the potential of gasified biomass. Nevertheless, it should be clear from reading the different chapters that the system builder is only one of several important actors and elements in the formation of a new TIS.

Pilot and demonstration plants have been emphasised as a key "tool" of the system builders for realising their intentions. The contributions made by institutes, universities, industry, and policymakers to system dynamics have been stressed. These actors can take on the role of system builders, but they also make other important contributions to system dynamics.

Understanding the contributions made by not only system builders but also these other elements in the emerging TIS structure is important for the discussion of policy options (Chapter XI) and for drawing more general conclusions with regard to implications for policymakers and system builders (Chapter XII).

The specific contributions made by system builders to system dynamics was analysed at great length in Chapter IX and will therefore not be repeated here. Instead, the first section will start by analysing the contributions to system dynamics made by demonstration plants, for example, how they are used by the system builders to form networks. In the second section, the contributions of, and relationships between, universities and institutes will be discussed. It is followed by an analysis of industry's different contributions and the relationships between the large incumbents and smaller entrepreneurial firms. The fourth and final section analyses the role of policy as a "midwife" in the creation of new industries that can realise the potential of new fields of knowledge.

10.2 Demonstration plants

The primary tools of the system builders for realising their intentions are pilot and demonstration plants. These plants provide a critical contribution to the dynamics of the TIS. In Chapter II, these contributions were summarised based on previous literature. In particular, Karlström and Sandén (2004) argued that demonstration projects are a special type of *materialisation* that is central to the industrialisation of new knowledge fields. For example, they can play a key role in the formation of knowledge networks, in reducing technical uncertainties, and in facilitating learning that can be used to support decisions on technology choice. In addition, they can raise public awareness of the technology, strengthen its legitimacy and expose system weaknesses such as various institutional barriers. Since different actors with a common interest come together in demonstration projects they can form a potential base for creating advocacy coalitions that can address these barriers. Demonstration programmes can also strengthen *market formation*—being a first protected market—even if the larger institutional context does not support the diffusion of the technology (cf. Kemp et al. (1998)). These observations are valid also in the case of biomass gasification.

In addition, this study has shown how demonstration plants are of pivotal importance as a tool for the system builders to align the emerging technology to the organisational, institutional and technological structure, as well as the physical infrastructure, in which they are embedded. This alignment is, of course, necessary in order to obtain the benefits listed above.

In Austria, the system builders aligned the technology to the small-scale district heating systems, hitherto not used for electricity production. They also made use of, and aligned, the technology with the EEG framework to strengthen *market formation* for less advanced application while experimenting with more advanced. Initially, they also managed to create an alignment with the complementary competencies of the major capital goods supplier in Austria, AE&E. However, the alignment was undone due to exogenous events beyond the control of the system builders.

In Germany, the demand for large volumes of renewable fuels has made it possible to launch two projects for the large-scale production of second-generation transportation fuels. The system builders have aligned the technologies to the interest of the agricultural sector, the automobile industry, the oil and petrochemical industries, as well as to some of the main capital goods suppliers of these industries by focusing on increasing the value of farm residues (FZK), providing infrastructure ready fuels, and adapting the biomass to existing gasifiers and down-stream processes used by the capital goods industries for gasification of fossil fuels and fuel synthesis.

In Sweden, it has been most challenging for system builders to align the technology to various interests. Black liquor gasification was “discovered” as a promising opportunity in the mid-1980s, but it was not well aligned with the interest of the pulp and paper industry. The industry was sceptical with regard to replacing their recovery boilers, which are at the heart of a chemical pulp and paper plant, with a novel and untested technology (Bergek, 2002; Modig, 2005). In addition, gasification of black liquor at the high temperatures of an entrained flow gasifier creates an extremely corrosive gas, which caused major material problems for the system builders.

However, due to extensive experimentation in various pilot and demonstration plants over a long period of time, the system builders appear to have overcome the immediate technical problems. In combination with actions undertaken by the Swedish Energy Agency, Volvo’s interest in DME and the more recent crisis for the pulp and paper industry,[292] the system builders have been able to proceed with the process of creating an alignment between their technology and the interest of not only the paper and pulp industry, but also a wide range of national and international firms with complementary resources and competencies. Yet, it remains to be seen if the alignment process will be completed, as evidenced by the commitment of the involved industry to a commercial-scale plant.

In the late-1980s and early-1990s, an alignment process was initiated by Studsvik/TPS when they decided to pursue atmospheric BIGCC. The technology was aligned with the interests of

[292] The crisis has forced the industry to start looking for additional income streams (please see Chapter VIII for a longer discussion). Domsjö AB has also declared that it is willing to invest in a first large-scale demonstration plant.

municipal utilities and their smaller-scale district heating systems. However, it was not aligned with the intention of policy, which failed to provide sufficient financing for the technology to develop. Instead, the large utilities explored pressurised, large-scale gasification that was not well aligned with the district heating networks in Sweden. If it would have been pursued on a commercial-scale, only a few such large-scale plants could have been built.[293] When TPS and others tried to assume the system building role in 2000, they "inherited" Sydkraft's and Foster Wheeler's large-scale technology but with limited commercial rights. In combination with a lack of national capital goods suppliers to collaborate with, these structural barriers became overwhelming for the system builders in fluidised bed gasification, and the process of aligning the technology to various interests failed to develop.

In Finland, all past and current demonstrations have been closely aligned with the interests of the incumbent boiler and pulp and paper industries, as well as the physical infrastructure of Finland with large heat sinks and an extensive supply of forestry residues. Small steps in the technology development have been taken by the actors experimenting with more and less advanced application of the technology since the 1970s. High-risk projects that would require extensive government support, such as the pressurised BIGCC technology, have not been pursued.

Only more recently, with the crisis of the pulp and paper industry, high-risk projects have also become sufficiently interesting for the Finnish pulp and paper and capital goods industry. For the development of second-generation fuels, in line with previous experience and the interest of the existing industry structure, the system builders have decided to develop fluidised bed gasification integrated in the pulp and paper industry but without the intention of replacing the recovery boiler. This reduces, of course, greatly the risk for the involved pulp and paper firms.

Thus, the individual designs of the various demonstration plants are a result of highly path-dependent processes in which technology choices are heavily influenced by the background of the system builders in combination with the local and national characteristics of the

[293] It has also been argued that the utilities did not take on a system building role.

physical environment, the interests of incumbent industries, and institutional structures. Nevertheless, this does not mean that demonstration plants are sole results and images of an existing structure. Instead, they should be seen as a means for actors from various complementary knowledge fields to test new combinations, thereby beginning to build new types of structures. As a result, nine rather different demonstration projects have emerged in the four countries.

These demonstration plants may be divided into two main categories. The first category of plants fulfils "just" the purpose of demonstrating a certain application on a large but sub-optimal scale of operation. Examples of such plants are Choren's demonstration facility being constructed in Freiberg and the Värnamo facility used for demonstrating BIGCC.

For a number of reasons, the risks of pursuing such plants are large. They are expensive to construct and they are likely to overrun budgets, as the development of novel technologies is highly unpredictable. Once constructed and in operation, these demonstration plants do not generate any, or only very small income streams, which discourages the undertaking of extensive experimentation as each hour of experimenting is costly. In addition, the afterlife of such plants may become problematic if it is not planned from the beginning and if the next step in the development is not pursued. Nevertheless, the construction of such demonstration plants may be unavoidable for certain applications, technology choices or when shifting from smaller to commercial-sized demonstration plants.

The second category of demonstration plants is the plants that, more or less, carry their own operating costs. These plants allow for continuous experimentation with more and less advanced applications and various feed-stocks whilst gaining operational experience. Examples of such demonstration plants are the gasification plant for combined heat and power production in Güssing and at Chalmers in Göteborg, and the lime kiln plant in Varkaus. An additional such plant is under construction in Göppingen. In all these plants, experiments with more advanced applications are made based on slip streams, recirculating the gas to a main application. With this set-up, extensive experimentation is encouraged and the development of more advanced applications can be pursued at a lower cost than in the first category. However, finding opportunities to construct such plants may, of course, be difficult and not even possible for all trajectories, scale or applications.

Demonstration plants have the potential of strengthening all functions, but they are particularly important for strengthening the "know how" functions of *knowledge development, entrepreneurial experimentation* and *materialisation*. Once constructed, they become part of the science and technology infrastructure. The existence of such an infrastructure is fundamental for continuing with new experiments and drawing lessons from successes and failures, thereby progressing the knowledge field towards more advanced applications.

In addition, strengthening the "know how" functions is essential in the industrialisation of an emerging knowledge field, as the actors involved develop an expert level of "know how" in new plant constructions and operations. In large-scale demonstration plants, this includes the development of an industrial capacity along the entire value chain.

To build such a capacity involves not only the construction of one plant, but of many plants for various applications and in many different scales. As others have illustrated, developing this capacity may take decades and the risk of failure is always present (Carlsson and Jacobsson, 1997; Grubler, 1998; Breshanan et al., 2001; Wilson, 2009). Arguably, it is of fundamental importance that the system builders (including capital goods industry) are embedded into an environment that allows them to experiment, fail and have the chance to learn from their failures.

10.3 Institutes and universities

Throughout the four case studies, the contributions of institutes and universities to the dynamics of the TIS have been emphasised. For example, it was illustrated that a university professor in Vienna took on the system building role (Chapter V). This particular individual appeared to have been exceptional in his capacity to build structure and strengthen the various functions of the TIS. His role and "usefulness" in progressing the TIS foremost concerned a capacity to create international knowledge networks, set up experiments on laboratory and demonstration scales, extend and combine design spaces into a new knowledge field, finding new applications, but also for diffusing the knowledge by offering consulting services. In addition, he managed to perform many of the tasks usually expected by a university professor such as publishing and examining students on Masters and Ph.D. levels. Ultimately, he also contributed to building a future human capital base from which companies in the field can recruit. Nevertheless, it is worth noting that although Professor Hofbauer accomplished extraordinary things, he never started a firm and has been granted only a few patents.

For an individual to take on such a system building role should perhaps be seen as quite extraordinary. In the three other cases, academia has taken a somewhat different role in the development of the TIS. In Germany, the universities have contributed by developing, for instance, models and simulations, for understanding the basic science of the various processes, in addition to various types of system studies of the technologies. An attempt to contribute to process development was taken at Freiberg University, which developed a new design of the pressurised high temperature Winkler gasifier and intended to construct a large pilot plant. So far, that project has failed, and process development and other activities associated with the system building role have primarily been done by institutes (see Chapter VI).

ZSW, FZK and CUTEC are three institutes who search for and develop opportunities across various knowledge fields relevant to the new TIS. By drawing on the general structure, both in Germany and internationally, institutes have acted as "catching-up learners" (Dalum et al., 1992; Lundvall and Johnson, 1994) within the German national innovation system. In so doing, they have focused on process development, setting up laboratory and demonstration plants, as well as taking on the system building role by setting up alliances with potential capital goods suppliers and customers. The system building role, thus, appears to have become institutionalised, as the institutes have taken on the responsibility to support and improve the competitiveness of industry not only along established trajectories, but also for finding and creating new business opportunities in promising areas.

In Finland, the institute VTT has to a lesser degree been a system builder since it has been part of a network with established actors interested in experimenting with the knowledge field for a wide range of applications. Instead, the most important role of VTT has been as a node and system memory within the Finnish TIS. Although private firms have largely undertaken process and technology development, VTT has participated in the main gasification projects in various industry collaborations both in Finland and in Sweden since the 1970s. It has, therefore, had a unique opportunity to learn from successes and failures. VTT has also been able to build a science and technology infrastructure in their laboratories, which has enabled further learning. Additionally, as a result of long-term basic funding, VTT has been able to continuously conduct various types of experiments, thereby advancing the knowledge field even when private actors' interest in the technology has been low. Consequently, when an industrial interest in gasification re-emerged with alternative fuels, VTT could play out their role as a system memory by setting up a research project (UCG) and quickly assessing how the technology could best be pursued for the new purpose. In addition, by setting up the research project and inviting all relevant industrial partners, they could be a node in the system, enabling the formation of two competing alliances (see Chapter VIII).

In national contexts where there exists both strong institutes and universities competing in similar arenas, such as in Germany and Finland, there is a risk of a tension between the two types of actors. For example, since VTT focuses on applied research and process development in collaboration with industry in similar areas as the universities, there is a risk of "cannibalising" the university sector. However, within this particular knowledge field, a division of labour between the universities, institutes and firms appears to have been created during the Jalo and Liekkie research programmes. In this, the strong position of VTT has forced the academic units to focus and become even stronger on basic and pre-commercial research in order to attract funding (Fogelholm, 2008; Hupa, 2008).

In the case of Sweden, a similar division of labour was created between the national research and development laboratory in Studsvik and at the Royal Institute of Technology (KTH) in the 1970s. Studsvik focussed on research on process development and KTH on basic research. However, when all of the research-related activities in the field of renewable energy were terminated at Studsvik by Vattenfall, there was no longer a public actor in the field of fluidised bed gasification taking on the role of experimenting with process development. Moreover, the spin-off company from Studsvik, TPS was later excluded from all collaborations with Vattenfall and Sydkraft.

Hence, a hole in the Swedish structure was created where no actor (institute) existed that could take part and learn from major demonstration- or commercial-scale projects. Instead, VTT partly took on that role in Sweden.[294] As a result, when the interest in fluidised bed gasification for transportation fuels re-emerged in the early-2000s, the universities were the only possible option to host the development projects. Hence, Växjö University created a holding company, VVBGC, for owning the Värnamo plant and coordinating research programmes. However, it clearly did not see that as its role—nor was it expected—to undertake system building activities or set up semi-commercial projects based on the research taking place.

In the field of black liquor gasification, the research institute ETC has recently become an important partner for hosting large-scale experimental research equipment necessary for process development, while the participating universities have focused on basic science and system studies. The most well-known laboratory or demonstration equipment has, of course, been Chemrec's black liquor gasifier but with the experience gained by participating in the development, ETC has been able to start experimenting in related fields and setting up collaborations with other actors.

Hence, universities and institutes have important contributions to make to the dynamics of the TIS. They:

a) act as "catch-up learners" and translate opportunities between different contexts (Lundvall and Johnson, 1994);
b) set up alliances with technology suppliers and customers, create knowledge networks, and learn over an extended period of time from past experiments, thereby becoming the "system memory";
c) host a science and technology infrastructure of large-scale experimental equipment;
d) can become a node for further experiments extending the design space into other areas; and

[294] This "hole" in the structure has overtime been filled by Swedish-based actors such as the department of Energy technology at Chalmers (see Box 7.1, Chapter VII) and the institute ETC (see Box 7.2, Chapter VII).

e) educate future experts within the field and conduct basic research, as well as system studies.

In the emergence of a new technological field, these two actors must deal with a complex set of tasks contributing to system dynamics. When possible, it is suggested that it could be beneficial for the two actors to seek and specialise in the undertaking of different types of system building and system supporting activities. In the above-mentioned cases, the institutes appear to have primarily focused on activities of system building and process development, as well as hosting large-scale experimental equipment, while the universities have focused on education, basic science and system studies.

10.4 Industry

The fourth contributor to system dynamics has been industry. For example, Repotec has so far dominated the industrial involvement in the Güssing project in Austria. As it is a small spin-off company (from AE&E), Repotec cannot take on large contracts by providing the required financial guarantees. It is therefore dependent on creating alliances with larger actors. Although potentially mutually beneficial, such an alliance could not be sustained with AE&E, since they had a booming business in their conventional technologies after their re-construction. AE&E had, therefore, no incentives to set resources aside for a new and uncertain alternative technology, which they considered to be outside their current scope of business.

In addition, Repotec was dependent on the EEG law supporting innovative CHP technologies. However, an alliance of incumbent industries in Austria, including the pulp and paper industry, managed to change the EEG law. Due to the weak functions of *legitimation* and *direction of search* in support of biomass gasification, both AE&E and the pulp and paper industry focused on improving the conditions for their current businesses instead of looking for new opportunities, which Repotec and the Güssing facility potentially could have offered.

If Repotec, Professor Hofbauer at TU Vienna and the Güssing facility symbolise the possibilities of renewing the established industry structure in Austria, then institutes and the start-up company Choren carry the same symbol in Germany. All the institutes included in this study, as well as Choren, have identified from the start the need to create alliances with capital goods suppliers and potential customers with complementary competencies, in order to take the next steps towards commercialising the technology. For example, FZK never considered it an option to create a new firm with the competence necessary to take the technology to the market, or for Choren to start developing new FT diesel catalysts (see Chapter VI).

Compared to the Austrian system builders, the German actors have been more successful in creating alliances and setting up common development projects with national industries, arguably due to the focus of Volkswagen and Daimler on promoting FT diesel as an alternative fuel over first-generation fuels. Due to their involvement, further resources could be mobilised to the field, not the least by setting up the EU project RENEW.

Despite the automotive manufacturers' strengthening of *legitimation* and *direction of search* in Germany, the incumbent capital goods industries with complementary knowledge in gasification and downstream synthesis processes have been reluctant to enter the TIS. Future Energy was only willing to engage in developing the field when it had spare capacity. When Future Energy was acquired by Siemens and coal gasification boomed in China, it lost interest in the field. Uhde has also been reluctant to enter for similar reasons. In addition, both firms referred to the high costs of developing the technology and the market, lack of paying customers, and dependency on government support for the technology to be competitive.

Nevertheless, FZK managed to convince Lurgi to take a major role in developing the technology. Lurgi already had experience with supplying equipment for first-generation fuels and could, based on its experience, identify a future market for second-generation fuels. In addition, Lurgi could find synergies between developing the option provided by FZK and the development of its future business in coal gasification (Chapter VI).

Hence, although they have been reluctant at times, the incumbents provided complementary resources and competencies to the institutes and to Choren, gradually taking over technology development and taking the first steps towards enabling a renewal of the established industry structure in Germany.

In Sweden, development has been dominated by the small firms Chemrec and TPS, acting in networks supported by the Swedish Energy Agency. The capital goods supplier Götaverken-Kvaerner was involved in the development in the 1980s and 1990s but was weakened over time. More recently, it was taken over by the Finnish capital goods supplier Metso. Since 2000, no major Swedish-based capital goods supplier[295] has taken part in the development by providing resources and complementary competencies. Nevertheless, Chemrec has been able to compensate for the lack of national capital goods suppliers. Backed by Volvo and the Swedish Energy Agency, it has been able to create alliances with European-based firms and the domestic pulp and paper industry for taking the necessary steps towards demonstrating the technology. Despite a similar type of backup, TPS was not able to compensate for the lack of industry structure and, due to also other circumstances, the recent plans for the Värnamo facility have so far not been realised.

Hence, Chemrec, TPS and other actors with an interest in exploring new technological opportunities—within the field of biomass and black liquor gasification—were not able to find complementary resources and competencies in a national capital goods industry that can appropriate on the knowledge development. This means that the Swedish structure has a hole not only in the form of a lack of an advanced institute (working on the fluidised bed trajectory), but also in the form of capital goods suppliers.

The development in Finland resembles Germany more than Austria and Sweden. However, it differs on one important point: the renewal of the incumbent industries (capital goods and pulp and paper) has, to an even greater extent than in Germany, taken place with an established network of actors, working within the design space of fluidised bed combustion.[296] This network of actors has, with the support of the government, experimented with biomass gasification in common development projects for various applications and various types of biomass feed-stocks since the 1970s. Thus, it has been able to set up common development projects for renewing industry by extending the design

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[295] Metso Power has activities also in Sweden such as sales, production, service and administration. However, most of the research and development is located in Finland, where it also has its head-quarters. Source: www.metso.com, accessed 2010-11-05.

[296] Except for Carbona, which was formed when Vattenfall pulled out of Enviropower in the mid-1990s, the industrial renewal has not taken place through the creation of new actors (such as Repotec, Choren, Chemrec and TPS).

space to also include biomass gasification, just as it had previously done for the development of innovative paper machines and for the fluidised bed combustion technology (Chapter VIII).

As the Swedish case has illustrated, for succeeding with this type of development project, a strong national-based capital goods sector is pivotal. Institutes, as well as small and innovative firms, are dependent on creating alliances with the incumbent industry for supporting projects with financial resources and complementary competencies. On the other hand, the incumbents appear to be locked into established businesses and seem to be dependent on institutes, universities and start-up firms to actually take on the role of developing and exploring new opportunities.

10.5 Policymakers

From an evolutionary perspective, policymakers should concern themselves with two main intervention alternatives. The first alternative concerns stimulating knowledge development and strengthening the innovative capabilities along existing and dominant knowledge trajectories. Along these relatively stable trajectories, knowledge is accumulated through incremental innovation and continuous improvements (Dosi, 1982). It has been argued that supporting the continuous improvements along well-established trajectories is what industrial policies often end up doing (Lundvall, 1992; Lundvall and Johnson, 1994).

The second alternative involves the more demanding task in which policymakers actively stimulate the creation of variety and knowledge development outside the dominant trajectories. This involves making it easier for agents to shift from one trajectory to another, thereby stimulating the creation of new industries (Lundvall, 1992; Malerba, 1996; Metcalfe, 2004).

In the formulation of industrial policy, policymakers are prescribed the important role of "re-formulating the rules of the game", thereby taking on the role of a "midwife" in the creation of new knowledge fields and industries (Edquist, 2002). In addition, it has been emphasised that policymakers—acting as "midwives"—should focus on creating winners and not "picking" them (Carlsson and Jacobsson, 1996; Lundvall, 2007).

This is, however, not to say that policymakers in the four countries have succeeded in acting as midwives with respect to biomass gasification, although attempts have been made to play that role in all of the case study countries. In Austria, with the help of Professor Hofbauer, policymakers could identify biomass gasification as an innovative technology, which had the potential to contribute to realising Austria's ambitious environmental targets. Consequently, a competence centre, RENET, was created. It provided long-term financial support, which allowed Professor Hofbauer to build a larger research group, as well as international collaborations to perform research. RENET also supported the collaborative research of Repotec/AE&E, the plant operators and the researchers at the Güssing facility, which resulted in a rapid technology development. Finally, the construction of the demonstration and research facility in Güssing would not have been possible without the support framework for renewable electricity (EEG).

During the time when AE&E experienced a down-turn in its market for combustion technology, the incentives provided by policy were sufficient for them to engage in the technology development of the gasification alternative. However, just a few years later the EEG was changed and AE&E experienced a booming business for conventional boilers. These changes weakened *direction of search* and *legitimation*. The incentives provided by the government were, by then, no longer sufficient to make the incumbent industry interested in participating in the knowledge development taking place at Güssing, and for potential customers in Austria to build similar types of plants. As a result, the actor structure was weakened and there are currently limited possibilities for Austrian-based actors to appropriate on the technology development taking place. Arguably, the policymakers in Austria had excellent opportunities to act as a midwife, but they missed out when changes were made to the EEG without providing exceptions for innovative technologies. In addition to these changes, further incentives would probably have been necessary for attracting the incumbent industry to take part in the technology development, thereby strengthening the Austrian TIS (Chapter V).

In Germany, on the other hand, the necessary industry structure is in place for appropriating the benefits of knowledge development. Policy has supported a wide range of experiments in biomass gasification with both technology-neutral support programmes such as regional development funds and innovation programmes. Furthermore, it has supported more technology-specific instruments such as the EEG and investment support from FNR, BMELV and regional governments. In addition, targets provided by the German government have often been more ambitious than the targets at the EU level, providing a stronger *direction of search* to the firms than in the other countries included in the study. Arguably, policymakers in Germany have attempted to take on the role of midwives, as they have played out a wide range of instruments necessary for “creating winners” without “picking them”.

However, policy has supported experimentation with biomass gasification only since the 1990s. Consequently, only limited experience has accumulated in Germany based on experiments with less advanced applications, at least compared with the situation in Sweden and Finland. In addition, even if the support has been substantial, no special provision guaranteeing a market for second-generation fuel in Germany has been created. Hence, there is no policy framework in place that supports the construction of plants beyond the initial demonstration phase.

Since the 1970s, Swedish policy has promoted and identified the use of biomass, peat and black liquor gasification as a strategically important knowledge field for reducing oil dependency, the dependency of nuclear power and for abating climate change. However, the support has exclusively been in the form of investment subsidies and research and development support. No programmes strengthening *market formation* have been initiated beyond the CO_2 tax introduced in 1991 and the green certificate scheme in 2003. However, for biomass gasification, such market incentives have made no real difference and have not allowed the technology to develop its potential.

In addition, from a national perspective, strategic mistakes were made when the municipal-owned utility Sydkraft and the state-owned utility Vattenfall were “allowed” to strengthen the TIS in Finland instead of building on the knowledge developed by Studsvik and Götaverken in the 1970s and 1980s. Compared with the situation for Chemrec, resources spent on fluidised bed gasification were not used to strengthen an actor and technology structure that remained in Sweden, including actors that could learn from mistakes.

The lack of an actor structure in Sweden has forced the Energy Agency to take on a very active role, supporting the remains of a structure in fluidised bed and black liquor gasification. The lack of actor structure has made it difficult to pursue a policy in which winners are created. Instead, policy has tried to pick winners by allocating significant resources to Chemrec and Värnamo. Without these actions, it is likely that Chemrec would have been forced to exit the TIS, and a new and vital structure for biomass gasification would not have been under development in the northern part of Sweden.

Similar actions were undertaken by the Swedish Energy Agency to save the Värnamo plant and create an industry structure for commercialising FB gasification for the production of transportation fuels. However, it proved too difficult mainly since Vattenfall and Sydkraft had not supported the development of a national industry capable of commercialising the technology in the 1990s. The hole in the industry structure made later rescue actions next to impossible (Chapter VII).

Hence, Swedish policy has failed on two accounts. First, it has failed to create niche markets for the technology to mature, which would have been of particular importance after the successful demonstration of the Värnamo plant. Second, it has failed to support the development of an actor structure that can learn from its mistakes. However, by having the courage to actually "pick winners", this weakness may have been successfully addressed in the case of black liquor gasification.

The role of policy in Finland has been dominated by a set of long-term research and development programmes that were initiated in the mid-1980s. The purpose of these programmes was to increase the level of knowledge and the competitiveness of the national industry for using peat and biomass in electricity production. A strategic goal was set for industry to develop its exports of power generating equipment to equal the value of the imported energy to Finland by 2000. In addition, policy has supported continuous experimentation with biomass gasification for various applications on demonstration and commercial scales. With funding provided by the government, the institute VTT has been able to participate in nearly all of the development projects, learn from its experiences, and develop a role as the system memory and node for future developments.

By the end of the 1990s, the actor and technology structure in Finland for pursuing BIGCC were probably the best in the world, but further technology development was necessary. For overcoming technical uncertainties, a market creation programme complemented with substantial investment subsidies exceeding the existing would have been necessary. Such incentives were, however, not provided.

Policy in Finland has, just as in Sweden, never supported new technology development with market creation programmes, beyond a few demonstration plants and investments subsidies. Hence, policy has not attempted to take on the role of the midwife in the creation of new industries. Policy in Finland has instead primarily taken on the role of stimulating experimentation and knowledge development along given trajectories. It has also been conservative with incentives that would risk increasing the price of electricity and reduce the competitiveness of dominant industries.

As previously mentioned, the main role of policy is that of a midwife in the creation of new industries, and their main task is to help build an environment that supports the creation of future winners. In so doing, it is of pivotal importance that a rich and heterogeneous technological, organisational and institutional structure is stimulated. Such a structure is central for the emergence of system builders and for them to draw resources, create alliances and develop new opportunities across various technological fields.

Industrial policy formulated with the intention of stimulating the creation of variety and knowledge development outside the dominant trajectories is an inherently uncertain process in which failure is an important and inevitable part. It has, therefore, been argued that industrial policy should leave some room for experimentation and "calculated failures" (Smits and Kuhlmann, 2004). As, Lundvall (2007, p. 38) states:

> *"...losers will become winners later on because they learn from the experience."*

The outcome and value of such failed experiments is in turn highly unpredictable, but can form a base on which valuable lessons can be drawn for policymakers, entrepreneurs and other actors involved. Therefore, it is not necessarily a contradiction between effective policymaking and failed experiments.

To support the emergence of a rich and heterogeneous structure, it is therefore suggested that policymaking should shift from having a short terms focus of succeeding with individual projects (which of-course is also important) to focus on strengthening an emerging actor and technology structure. Hence, before policy finances projects in a new knowledge field, it is necessary to identify (see Chapter VII):

a) what type of science and technology infrastructure is created. Is it useful beyond a single experiment or demonstration and, if so, who can continue to learn from it?

b) who has the ability to appropriate the benefits of the knowledge development, even if the project itself fails?

In order to ensure that there are firms that can appropriate the benefits of knowledge development, policy must tend to the survival of the capital goods industry as it strongly contributes to maintaining a rich and heterogeneous structure, which the system builder can draw upon. Without a prosperous capital goods industry, universities, institutes and technology-based venture firms will have limited opportunity to leverage technology developed in the market. In addition, national funding agencies will have limited prospects of finding that their efforts actually lead to the creation of new growth industries. It is, therefore, argued that the EU may have a particularly important role in identifying and supporting system builders that are embedded in weak national industry structures, enabling them to build alliances with international actors with complementary resources and competencies.

For system builders to be able to create alliances with an existing capital goods industry, it was emphasised that incumbent industries often need strong incentives to explore new areas outside their current business scope, especially when they are doing well in established areas. Incentives to experiment and explore radically new areas are often given in terms of investment, research and development subsidies. However, since it was demonstrated that the system builders are limited in their capacity to strengthen market formation through institutional alignment (Chapter IX), programmes must be designed to create, at least temporary, markets for immature technologies. The combination of investment, research and development support with programmes designed to create markets should be constituted so that some of the technical and market risks involved are alleviated and allow the technology to mature (cf. Kline and Rosenberg (1986)).

For such incentives and programmes to be effective, they must consider the specific contextual conditions required for a new technology to emerge, mature and have a chance to realise their long-term potential. Hence, for industrial policy to be meaningful it must include significant technology-specific elements. From this perspective, generating the actual "content" of an effective industrial policy involves analysing who the potential system builders are in various important technological fields, the structure in which they are embedded, as well as the nature, extent and limits to their transformative capacity.

10.6 Conclusions

In this chapter, the contributions of demonstration plants, universities and institutes, and industry and policy to system dynamics have been discussed.

The discussion started with identifying demonstration plants as the primary tool for the system builders in realising their intentions. These plants are used for aligning various interests, drawing resources from the structure, creating alliances, experimenting with technology options, creating an initial market, etc. Indeed, the fundamental task of the system builder is to align the technology to the specific context in which he/she is embedded. This means that the technology pursued and the plants constructed are not a matter of what is primarily perceived as optimal from a technical or environmental perspective, but rather what is possible to pursue from the perspective of the system builders in relation to their backgrounds and the contexts in which they are embedded.

Individuals at universities and institutes contribute to system dynamics by taking on the role of system builder, but they also contribute in other ways. It was shown that some of the German institutes have institutionalised the system building role, and act as "catch-up learners"—translating technological opportunities from one context to another. In Finland, the institute VTT did not act as a system builder but took on the role of a "system memory", having participated in and gained experience from almost all major gasification projects in Finland, and some in Sweden, since the early-1970s. Having that type of experience enables them to also become an important node for setting up future collaborative projects within the field. The institutes and universities also contribute to system dynamics by hosting a science and technology infrastructure, conducting basic research and system studies, and educating the engineers and experts necessary for the TIS to expand in the future.

In the case of biomass gasification, most of the entrepreneurial experiments have taken place at universities, institutes and in small entrepreneurial firms. However, for commercialising the knowledge field, these actors are dependent on the resources and complementary competencies of the incumbent capital goods industries and other large actors along the entire value chain. Without the participation of an established industry structure, the entrepreneurial activities undertaken at the universities, institutes, and start-up companies will not be leveraged into commercial opportunities. Since the system builders primarily draw resources from the local contexts, countries with a rich and heterogeneous industrial structure will have a competitive advantage over countries with a poor and homogenous industry structure.

In contributing to system dynamics, the primary role of policy is to act as a "midwife" for an emerging TIS. Taking on that role involves tending to a structure that supports the creation of future winners. For supporting such a structure, it was concluded that policy should focus on what type of science and technology infrastructure that is created, if it is useful beyond a single experiment or demonstration and, if so, who can continue to learn from it. Clearly, policy needs to identify who has the ability to appropriate the benefits of the knowledge development even if the project itself fails.

For policy incentives and programmes to be effective, it was further suggested that the specific contextual conditions must be considered and reflected upon. Such policymaking departs from the potential system builders in important technological fields and analyses the structure in which they are embedded, as well as the nature, extent and limits to their transformative capacity.

As of yet, and as was specified in Chapter IX, the system builder have been limited in their capacity to turn the current "system building" motor into a "market motor" by aligning the institutional framework (Suurs, 2009). Consequently, in none of the case study countries have policymakers taken on the role of the midwife by supporting market formation beyond the first demonstration plants, thereby, facilitating the large-scale diffusion of second-generation fuels. In Chapter XI, the main policy options for shifting the field from the formative phase to a growth phase will be outlined.

Chapter XI
Policy challenges for completing the formative phase

In Chapter I, the overall purpose of the thesis was formulated as to

" ... analyse the role of the system builders in the emergence of an industry with the capacity to realise the potential of gasified biomass for the production of second-generation transportation fuels and other chemicals within the European Union."

Four research questions centred on the system builders were formulated and were answered in Chapter IX. Chapter X provided reflections on the contributions to system dynamics by actors and elements of the structure other than the system builder. Based on the previous analysis it is now possible to provide a short answer to the fundamental question formulated in Chapter III: " *... have the past 200 years of fossil fuel gasification, and the recent decades of experiments with biomass as a feed-stock for less advanced applications, created the industrial capacity necessary for commercialising the production of second-generation fuels based on biomass gasification?*"

The short answer to that question is: no, at least not yet. For such an industrial capacity to develop, two main system weaknesses at an EU level must be addressed by policymakers and system builders alike.

In Chapter IX, the system weaknesses were formulated as:

1) *" ... insufficient actor and technology structures in support of the development and diffusion of second-generation fuels."*
2) *" ... the lack of joint political network(s), advocating an alignment of institutions and technology."*

Since no second-generation fuel is produced from biomass, the actor and technology structure is—for different reasons—**not** sufficiently strong in any of the case study countries.

Addressing the first system weakness is of particular importance in Austria and Sweden (with respect to fluidised bed gasification), as system builders in these countries have difficulties forming alliances with incumbent capital goods suppliers, with complementary resources and competencies—which can appropriate the benefits of knowledge development. With regard to the second weakness, it was argued that political networks are of particular importance in Sweden and Finland, as there is a lack of an institutional framework that recognises the need for creating market preconditions in support of emerging technologies.

Resolving the first system weakness involves reducing the remaining technical uncertainties by building demonstration plants at a sub-optimal scale, as well as a few full-scale demonstration plants for each trajectory and taking them into operation. However, it also involves coordinating investments along the entire value chain and developing a wide range of complementary technologies. What these complementary technologies are depends on which of the three trajectories the system builders have chosen and which end product they intend to market. Therefore, completing the value chain involves resolving remaining organisational uncertainties as well. Hence, addressing the first system weakness involves resolving not only technical but also organisational uncertainties that currently discourage further investors from entering the TIS (see Chapter II).

For enabling the system builders to address the first system weakness and begin large-scale diffusion of the technology by 2020, the function of *market formation* must already be strengthened now. It involves aligning the institutional frameworks to the technology, thereby reducing institutional and market uncertainties that discourage investors to enter the TIS (see Chapter II). It is only after these four uncertainties are resolved that the formative phase of the TIS can be finalised and shifted to a growth phase.[297] So far, the system builders have been limited in their capacity with respect to achieving an institutional alignment, and if no further actions are taken in such a direction, it is likely that the TIS will remain in the formative phase well beyond 2020.

[297] Below, it will be argued that it is highly unlikely that a growth phase can begin before 2020.

Policymakers willing to take on the role of "midwives" must, therefore, act to reduce the structural constrains of the system builders by strengthening *market formation* through institutional alignment. If such an alignment can be accomplished, the market uncertainties associated with the second system weakness can be reduced.[298] In turn, this will provide incentives for actors with complementary competencies and resources to enter the TIS along the entire value chain, thereby reducing the organisational uncertainties.

The entry of further actors is necessary but not a sufficient pre-condition for shifting the TIS into a growth phase. The technical uncertainties associated with the first system weakness and in scaling up the technology from pilot/demonstration plants to the first semi-commercial and commercial-scale plants must also be addressed by policy.[299] Hence, to ensure that the TIS moves into a growth phase by 2020, the main task of policy is to address market uncertainties and remaining technical uncertainties facing potential investors.

Based on the previous chapters (mainly Chapters I and III), the technical uncertainties facing investors will be revisited in the following section. In the second section, an analysis will be presented of different policy instruments for reducing market uncertainties for investors, shifting them to society at large. A set of criteria for assessing policy instruments are developed and these are applied to a number of policy options. The third and final section concludes the discussion on policy.[300]

11.1 Technical uncertainties

The nine main projects are all in the process of moving from the pilot stage to constructing the first demonstration units (see Chapter III and Chapters V-VIII).[301] The cost of these first demonstration plants ranges from €1-100 million. However, not all of these first

[298] If market uncertainties are addressed by institutional alignment, the institutional uncertainties are thereby also addressed. The remaining discussion will thus focus on reducing market uncertainties as a key task for policy.

[299] Organisational uncertainties are assumed to be sufficiently reduced if the technical and market uncertainties are handled. The lack of an actor structure and other context-specific weaknesses that have been pointed at will not be handled here.

[300] Further implications for policymakers and system builders will be specified in Chapter XII.

[301] The exception is UPM and Andriz/Carbona, who plan to go from pilot to semi-commercial demonstration directly. Their pilot plant is, therefore, seen as their demonstration plant. The reconstruction of the Värnamo plant is currently on hold but there are still hopes to form an alliance with actors willing to take some of the required investment costs.

demonstration plants include the demonstration of the synthesis process, and they will be operated at a sub-optimal scale (see Table 11.1).

Table 11.1: Estimates of cost and time plan for the major development projects.

	Pilot		**Demo**			**Pre-Commercial Demo**			**Commercial demo**			**Cost**
	Year	*Cost (M€)*	*Year*	*Size*	*Cost (M€)*	*Year*	*Size*	*Cost (M€)*	*Year*	*Size*	*Cost (M€)*	€/l_{de}
TU-Vienna/Repotec	1995		2002	8+1MW	10	2013	160GWh	75	2015<	0.07Mtoe	150	0,7
Chalmers/Metso	2008	1.1	2008	6MW	1.1				2015<	0.07Mtoe	150	0,7
ZSW/EVF	2002	2.4	2010	10MW	18	2013<	10MW		2015<	0.07Mtoe	150	0,7
Chemrec	2005	7	2010	5MW/1.5kt	28	2012/13	0.1Mtoe	300	2015<	0.2Mtoe	400	0,5
Värnamo				18MW	45				2015<	0.2Mtoe	400	0,7
Carbona/UPM	2005	10				2011/12	0.2Mtoe	400	2015<	0.2Mtoe	500	0,5
FW/SE/Nesté			2009	12/5MW	40	2011/12	0.1Mtoe	400	2015<	0.2Mtoe	500	0,5
Choren	1998	NA	2008	45MW/15kt	100				2015<	0.2Mtoe	800	0,85
FZK/Lurgi	2005		2008	5MW	4	2011	5MW	70	2015<	0.2Mtoe	900	1
Total					***245***			***1245***		***1.41Mtoe***	***3950***	

Sources: Representatives from the different projects, as well as (Atrax Energi, 2002; Zwart et al., 2006a; Zwart et al., 2006b; Leible et al., 2007; Zwart, 2007; McKeough and Kurkela, 2008; RENEW, 2008; Thunman et al., 2008).[302]

The subsequent shift to pre-commercial demonstration plants and full commercial plants involves dramatic up-scaling of the size and cost of the plants. For instance, for the Chemrec plant (HT-EF gasification of black liquor in Sweden) this will involve an increase in output from 1.5ktoe in a demonstration plant that will be built by 2010 to 100ktoe in a pre-commercial plant (possibly constructed by 2012-2013) and to 210ktoe in a commercial plant to be ready to take into operation no earlier than 2015 (Rudberg, 2008; Domsjö, 2009). The investment costs would typically be between €400-800 million for commercial plants with a production capacity in the range of 0.2Mtoe (Thunman et al., 2008).[303]

As pointed out in Chapter III, there are substantial technical challenges and uncertainties facing investors. Throughout the up-scaling process, uncertainties of a technical nature are likely to remain although they are expected to be smaller as the up-scaling process proceeds. On the other hand, the sums involved are much larger, so technical uncertainties still constitute a serious obstacle to investment. Conventionally, demonstration plants receive investment subsidies from governments; however, risk absorption schemes may also be applied such as in the case of the Güssing plant in Austria (Hellsmark and Jacobsson, 2009).

[302] This is the same as Figure 3.4.1 in Chapter III. The intentions and time frames of the representatives of the different projects change quite frequently and the figures in Table 11.1 are often updated.

[303] The large differences concerning the investment costs in Table 11.1 are influenced by the large uncertainties involved, but they also depend on technological trajectory, end-product and possibilities to integrate and share costs with existing industry infrastructure.

In these schemes, funders absorb the risks by taking the loss if the project fails. This also means that banks don't have to add a risk premium.

Given the sums involved, any government programme must be very large, at least set in relation to other renewable energy technologies (with the exception of off-shore wind power). In the Swedish case, for instance, a new funding scheme for the demonstration and commercialisation of second-generation fuels and other energy technologies came into place in 2008 involving about SEK 875 million (€87 million)[304] over a period of three to four years (Swedish Energy Agency, 2008). This scheme represented a major increase in the availability of such funding. Through the above-mentioned scheme, Chemrec was granted SEK 500 million (€50 million) and Göteborg Energy (acting to realise the TU Vienna/Repotec technology) SEK 222 million (€22 million) to complete the pre-commercial demonstration phase (in Table 11.1).

Continuing with the case of Sweden, assuming that one plant from each of the three trajectories will be constructed in the next phase of commercial-sized demonstrations, an additional €1,000 million would have to be raised. To cover, say, 20 percent of the total investment, a demonstration funding scheme of an additional €200 million would therefore have to be made available. An obvious policy challenge is, thus, to devise policy instruments that can induce investors to face the technical uncertainties in moving to the first commercial plants.

Such a programme must have a long duration in order to be effective. Currently, almost all of the alliances are constructing, or attempting, to get their demonstration plant into operation. Table 11.1 indicates when the various alliances predict that their projects will pass through the different phases. The year refers to when they expect the various plants to be constructed and not when they will be taken into operation.

Based on the history of the field, these time plans are likely to be optimistic. For the Värnamo BIGCC demonstration plant, which was built in Sweden in the 1990s, it took approximately three years after its construction before it was operating with satisfaction and

[304] 1 SEK is approximately 0.1 EUR.

an additional three years to complete the demonstration programme (see Chapter VII). To produce synthetic fuels from biomass is a considerably more complex process than BIGCC. It may therefore be reasonable to assume that it will take at least three years, probably more, from when a pre-commercial demonstration plant has been constructed until any investor is willing to commit to a full-scale, semi-commercial demonstration plant.[305]

Hence, it is likely that no continuous production of synthetic fuel will be sufficiently demonstrated and technical uncertainties resolved before 2013-14 in the demonstration plants currently being constructed on a sub-optimal-scale. Hence, investors will be expected to decide on constructing the first pre-commercial demonstration no earlier than 2014. It may then take perhaps three to four years to construct and demonstrate the larger plants. The associated technical uncertainties may not be expected to have been resolved, allowing for an investment decision for the first commercial-scale plant in 2017-18. The first commercially and continuously produced synthetic fuel from biomass gasification can to be expected be available no earlier than about 2020.

Although perhaps unrealistic, assume that all of the projects in Table 11.1 are realised and at least one commercial-scale plant will be built for each project. The combined production capacity of these plants would then be approximately 1.4Mtoe. This amounts to less than 0.5 percent of the EU transport fuel market. Hence, whilst second-generation fuels may be available by 2020, one cannot expect the volumes to be significant by then.

In sum, the complexity and large-scale character of the technology for producing second-generation transportation fuels from biomass dictates that, from an investor's perspective, it is vital that policies involve not only substantial sums but also have a long-term horizon. The expected time scale involved in shifting from the current demonstration phase to a situation where second-generation fuels may have a significant impact on the market may also have to be adjusted (cf. IEA (2008), EC (2009a)), underlining the need to have a very long-term view of this process of transformation by policymakers.

[305] In the case of Repotec and Metso Power, the pre-commercial demo is the first demonstration of the production of BioSNG. The previous demonstration concerns electricity production.

11.2 Market uncertainties

There are very substantial uncertainties facing investors with respect to *market formation*, uncertainties that need to be handled if the potential of gasified biomass is to be realised. Two of these, the size of the potential supply capacity and the threat from substitutes, will now be discussed.

11.2.1 The size of the potential supply capacity

The current EU Directive, 2009/28/EC, mandates a 10 percent share of biofuels by 2020 for each and every member state (EC, 2009a). It translates into approximately 30Mtoe of the current fuel consumption.[306] With a maximum of 1.4Mtoe in 2020, the contribution of second-generation fuels to this goal cannot, as above-mentioned, be expected to be more than marginal.

Looking ahead and assuming that second-generation fuels capture a market of, say, 30Mtoe (approximately 10 percent of the current fuel market) by 2030, it would involve building 150 plants, each supplying 0.2Mtoe of fuel. The total value of the fuel supplied would be in the order of €15-30 billion per year and the total investment for building these one hundred fifty plants would be in the magnitude of €60-120 billion (see Chapter III).

Looking even further ahead to 2050, if gasified biomass "only" captures 25 percent of the current fuel market (77Mtoe), some 300-400 plants would have to be built at a total value of €150-300 billion.[307] Thus, a large-scale transformation of the fuel market would entail huge market opportunities for both fuel and capital goods suppliers.

However, and as was discussed in Chapter III, estimating the potential market for a new technology is always fraught with difficulties. Unlike many other technologies, a main factor is the long-term supply capacity. For three main reasons, it is difficult to assess how much

[306] In 2006, the use of biofuel amounted to 5.4 Mtoe, or 1.8 percent of the market (Eurostat, 2009).

[307] Since the figures are highly uncertain, potential learning effects were not considered. Some learning that would result in lower investment cost could, however, be expected for every doubling of installed cumulative capacity. However, in an overview by Neij (1997), large-scale power plants experience very little learning. In some cases, the cost may even increase with installed capacity, which was the case for nuclear and coal electricity plants. For smaller power plants, the investment cost was reduced with an average of 13 percent for each time the cumulative installed capacity was doubled (Neij, 1997). If learning will take place, one may assume that it will be at most 13 percent.

renewable transportation fuels can be produced through gasifying *domestic* biomass resources in Europe. First, it depends on how much additional biomass can be produced and if/when lower grade biomass and waste sources can also be used for fuel production. Social and environmental aspects associated with increasing the production of biomass are difficult to assess but need to be carefully considered.[308]

Second, it depends on what is perceived as a desirable allocation of the biomass potential to fuel production, as opposed to other uses of the biomass (e.g., supply of heat and power or bioplastics). Third, it depends on the thermal energy efficiency, for example the thermal energy ratio of turning biomass into fuel.

In Chapter I, a simple calculation was made to illustrate the impact of these three factors on the potential to substitute fossil fuel with renewable fuel based on gasified biomass. The main message is that this potential is highly uncertain, as the substitution potential varies between 6 and 56 percent. In terms of potential market size, the range translates to as low as 18 and as high as 173Mtoe.

11.2.2 Threat from substitutes

A second source of uncertainty stems from threats from substitutes. Investors that may eventually deliver second-generation fuels face a great deal of competition. They must compete not only with the lower cost first-generation biofuels (biodiesel and ethanol, etc.) but also with fossil-based alternatives[309] and conventional fuels (DENA, 2006; IES JRC, 2007).

With respect to conventional fossil based fuels, potential investors would, in the absence of a deployment policy, face very substantial market uncertainties for both the initial nine plants and for the subsequent 100 and more plants. These uncertainties are illustrated in Figure 11.2 (also found in Chapter III, Figure 3.4.6). In the Figure, three cost levels for

[308] On the other hand, the biomass potential would be expected to increase with increased use of biomass, as actors discover biomass resources to explore that previously had been unknown, underdeveloped and difficult to measure (Kåberger, 2009).

[309] Alternative fossil-based fuels, with the exception of oil shale, require a much lower oil price to break even than second-generation fuels from biomass. A higher oil price would, therefore, primarily induce a search for these fossil-based fuels rather than biomass based alternatives. A clear case in point is the massive interest for coal gasification in China, which attracts capital goods firms and others at the expense of developing biomass based solutions.

second-generation transportation fuels are distinguished: US$ 82, 140 and 165 per barrel. These cost levels were provided by advocates of the different projects and were explained in Chapter III.

They refer to estimated cost levels for the production of second-generation transportation fuels from biomass, taking into consideration the availability and cost of the domestic biomass supply, the production method, end product, and possible integration into existing industry infrastructures.

These cost levels can be set against past, present and predicted price levels for oil. The average world oil price from 1970 to 2009 was $35.59 in 2008 dollars.[310] In the World Energy Outlook, IEA (2009) predicts the real oil price by 2030 in two main scenarios. In the first, the reference scenario, it is set at $115 per barrel, and in the second, the high price scenario, it is raised to $150 per barrel (constant 2008 prices).

Figure 11.2 provides a base for assessing the financial magnitude of uncertainties caused by unknown future oil prices. It points to the hypothetic annual losses (or gains) for investors if a 10 percent BtL market (30Mtoe) is realised sometime in the future. Investors would lose almost $30 billion if that market was realised at a production cost of BtL of $165 per barrel and with an oil price at an historic average of $35 per barrel. On the other hand, with production costs of $82 per barrel of BtL and with the oil price at the predicted $150 per barrel, investors would gain substantial sums.

[310] Calculated by wtgr.com Accessed 2010-05-05

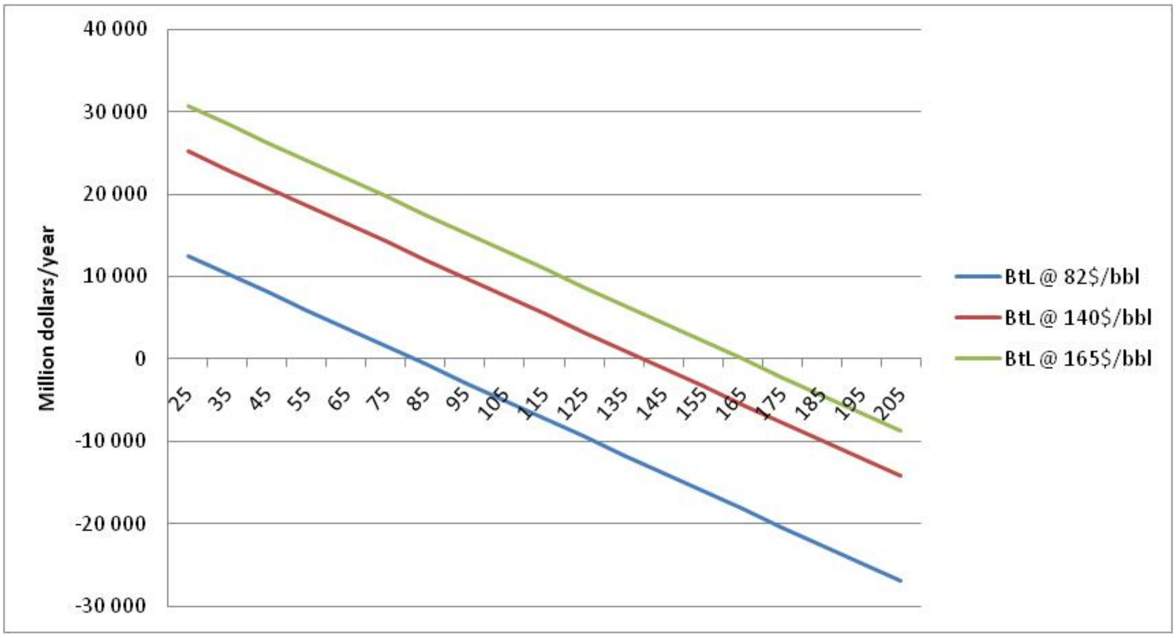

Figure 11.2: A tentative assessment of financial risk for commercial-sized plants—Annual cost of realising a BtL market (10 percent second-generation fuels from biomass) (M$).

In sum, there are substantial technical and market related uncertainties for all actors necessary to realise the potential of second-generation transportation fuels, including those in the capital goods industry, the refinery industry and among the transport equipment manufacturers. Moreover, these uncertainties are not of a short-term character but are expected to exist for many years ahead. Therefore, only very powerful and durable incentives may induce the necessary investments—including continued coordination between investors—to take the industry into a pre-commercial demonstration phase and, eventually, form significant markets for synthetic biomass-based fuels. These incentives not only have to induce investors to face technical uncertainties for a prolonged time period, but they also balance the cost differentials with first-generation biofuels[311] and manage the large market uncertainties with respect to conventional fuels. In the subsequent section, various policy options will be discussed.

311 A source of added complexity comes from alternative fossil fuels, the use of which leads to huge emissions as mentioned in the Introduction. Yet, many capital goods firms are attracted by markets for such fuels, for example in China, at the expense of developing the technology to gasify biomass.

11.2 Realising the opportunities of gasified biomass—an analysis of policy options[312]

Reducing technical and market uncertainties is the main challenge ahead for policymakers, and in this section various means of doing so in an effective manner will be discussed. The focus will be on market uncertainties since investment subsidies or risk absorption schemes (managing technical uncertainties) alone may not be enough to stimulate investments (about €4 billion) even in the first set of nine commercial-scale plants (see Table 11.1) due to the very large market uncertainties. Yet, the technical uncertainties must be handled as well, which will be returned to in the concluding discussion. Before discussing the usefulness of various policy instruments for forming markets, it is, however, necessary to specify the assessment criteria, in particular what "effectiveness" entails.

11.2.1 Criteria for assessing policy instruments

Effectiveness, efficiency and equity are three commonly used criteria for assessing policy options (Verbruggen, 2008; Jacobsson et al., 2009). The *effectiveness* of an instrument is assessed by its ability to meet a certain target, for example ten percent biofuel by 2020.

Efficiency, or cost effectiveness, often involves focusing on selecting the currently most cost-efficient technologies (see for instance the "Tradable Green Certificate Systems" in the UK, Sweden and Flanders (Jacobsson et al., 2009). There are two problems with this criterion. First, efficiency without effectiveness is meaningless: it makes sense to assess the efficiency of instruments only if they are expected to lead to the achievement of a certain target. To the extent that this requires the development and diffusion of second-generation transportation fuels, the effectiveness of any policy instrument must be assessed, as is evident from the sections above, by its ability to influence the strategic decisions of actors to explore and develop alternative technical solutions, fill the whole value chain and coordinate actions. This process of "putting gasified biomass on the shelf" (Sandén and Azar, 2005) has hitherto taken decades and we have still only reached the stage of smaller scale demonstration plants for more advanced applications. Unless it can be convincingly argued that all instruments are equally likely to be effective, the potential impact of these on the

[312] This chapter draws heavily on Hellsmark and Jacobsson (2010).

behaviour of the capital goods industry (and other actors in the value chain) and the associated impact on technical change must be scrutinised.

Second, minimising costs over several decades means that there is a need to focus on what policy instruments can be expected to generate the lowest cost solution over the whole period, again taking technical change into account. This rests, to a large extent, on the innovative capabilities in the capital goods industry. Hence, both effectiveness and cost effectiveness rests on the ability of various instruments to influence the capital goods sector and its ability to drive technical change.

The third criterion is *equity,* which is a crucial factor in creating social legitimacy for policies supporting new technology. Excess profits threaten legitimacy and must be avoided (e.g. European Commission (1999); Verbruggen (2008); Jacobsson et al., (2009); Bergek and Jacobsson (2010)).

In order to assess the effectiveness, as well as the cost-effectiveness of a policy instrument, a goal of the intervention must be specified. In broad terms, this goal is related to the need to greatly reduce GHG emissions over the next four decades. Of course, a diffusion of second-generation fuels is only one element in such a change, and a specific goal of diffusing second-generation fuels has not been set in the individual countries, nor at the EU level.

However, as mentioned earlier, a general biofuel goal of 10 percent of the European land transport fuel by 2020 has been set by the EU Commission, which would involve about 30Mtoe, up from 5.5Mtoe in 2006 (IEA, 2008, Table 7.2). Going beyond 2020, an aggressive strategy to cut emissions would involve a major increase in the supply of second-generation transportation fuels from biomass (IEA, 2008, p.473).

What goal should the "effectiveness" criterion be related to? Arguably, for the period from now until 2020, an initial goal would be to move from smaller demonstration plants to having full commercial-sized plants from the different trajectories up and running. In addition, whole value chains need to be formed. Hence, a first goal is to "put the various technologies on the shelf". Of course, given the range of uncertainties, it is possible that some of the experiments fail and that a specific technology turns out to be unviable. A broad set of experiments ensures, though, that not all will be failures. Having the various technologies "on the shelf" is likely to be achieved no earlier than 2020. This means that we expect it to take at least 10 years to move from the current small-scale demonstration plants to the first commercial-sized plants that can continuously produce a range of second-generation transportation fuels. As mentioned above, in terms of market share, these first plants would supply less than 0.5 percent of the EU land transport fuel market.

In the next stage, a goal for 2030 could, for instance, be set at 20 percent biofuel, out of which half could be second-generation. This would amount to about 30Mtoe.[313] As previously mentioned, this would involve building about 150 plants, which subsequently will be used as a second goal.

This means that policies must be assessed with respect to their ability to meet these two goals within the specified time frame. To be effective, we will argue that several alternative technologies need to be developed. This is, of course, inherent in the first goal but also, arguably, a necessity if the second goal is to be reached.

In contrast to many other industries—such as the automobile and consumer goods industries—the different technological trajectories do not represent conventional "competing designs", that is design configurations that can substitute one for the other (Utterback, 1994). The applications of the technologies in the three trajectories to specific contexts are more or less constrained in their potential. For instance, feed-stocks vary in their availability, for example the use of HT-EF with black liquor as a feed-stock is constrained by the number of paper and pulp mills with chemical process technology (in contrast to mechanical). Moreover, there are joint production opportunities in the paper and pulp, petro-chemical and district heating industries, but, of course, the opportunities for economies of scope are limited by the size of these industries.

The lowest cost level for producing BtL in Europe based on domestic biomass resources can be expected to be found in Sweden and Finland due to large volumes of forestry residues in connection with the pulp and paper industry, as well as large district heating networks in

[313] This is broadly in line with the 450 Policy Scenario in IEA (2008) if the EU maintains its share of the global biofuel market.

which the technologies (all three trajectories) can be integrated (Ekbom et al., 2003; McKeough and Kurkela, 2008; RENEW, 2008). The potential in a European market perspective is, however, quite limited. Ekbom et al., (2003, Table 7.1) show that the potential for FT diesel production using black liquor is about 2Mtoe for Sweden and Finland together. This would substitute for about 20 percent of the petrol/diesel consumption in these two countries. Even if production were to be doubled by the inclusion of fuel production in mechanical paper mills and district heating systems, meeting a goal of 30Mtoe by 2030, and going beyond it, would certainly require that the higher cost technologies and biomass resources would also need to be deployed.

With the long time axis of going from small demonstrations to full commercial plants—in other words putting the technologies on the "shelf" and the extension of that time axis in their subsequent diffusion—*effectiveness involves creating markets for all the three trajectories which then will develop in parallel rather than sequentially, jointly up-scaling the technologies and gaining market shares from fossil alternatives and not from each other*. Therefore, from a climate change perspective, the competition to focus on is between fossil-based (conventional and alternative) and biomass-based alternatives rather than between the three design approaches for using biomass as a feed-stock.

11.2.2 An analysis of policy instruments for reducing market uncertainties for investors

Having established a key criterion for assessing the effectiveness of various policy instruments, a number of such instruments that are either in operation or have been proposed to foster a market for second-generation transportation fuels will now be discussed. It will be assumed that the policy instruments operate at the EU level. The instruments are a general quota for biofuel (including first- and second-generation), separate quotas for first and second-generations and feed-in tariffs. Before turning to these, two other instruments will be mentioned briefly: tradable green certificates and the inclusion of the transport sector in the European Emission Trading System (ETS).

Tradable green certificates (TGC) are an instrument that has been heavily favoured by the EU Commission and other actors as a deployment policy in the field of renewable power

(Jacobsson et al., 2009). The core of this policy is, however, to select the currently most cost-efficient technology and only in a step-wise manner introduce more costly technologies. It is a policy instrument that deliberately abstains from creating a market for less developed, and higher cost technologies (Bergek and Jacobsson, 2010). Hence, it cannot be expected to fulfil the effectiveness criterion.[314] As for the inclusion of the transport sector in the ETS, it is obvious that the volatility of the price for emission permits and the highly uncertain future of the size of the cap create very large uncertainties for investors who have to estimate income streams over two or more decades. Hence, in terms of Figure 11.2, the market uncertainty is very high indeed which strongly discourages investments.

A *quota for biofuels* is currently operating in, for example, Germany. However, a general quota induces an expansion of the least cost options first, that is first-generation biofuels. Whereas the desirability of first-generation biofuels is questionable (in terms of both their ability to reduce emissions and their use of food crops and arable land), the potential is large, especially considering import opportunities from Latin America and Africa. A general quota would, therefore, not be a strong inducement mechanism for firms to invest in up-scaling and further developing second-generation biofuels.[315]

To stimulate such development, the European Commission has decided that the “ ... contribution made by biofuels produced from waste, residues, non-food cellulosic material, and lingo-cellulosic material shall be considered twice that made by other biofuels ... ” (EC, 2009a, Article 21:2). In addition, the EC proposes that when Member States design their support systems they may give “ ... additional benefits to ... biofuels made from waste, residues, non-food cellulosic material, lingo-cellulosic material and algae, as well as non-irrigated plants grown in arid areas to fight desertification ... ” (EC, 2009a, p.26). Hence, the Commission recognises that second-generation fuels will be considerably more expensive than first-generation and need additional support in order to develop.

[314] For a discussion of this point with respect to renewable power technologies, see Jacobsson et al., (2009). In that paper, there is also a lengthy discussion on the equity criterion and TGCs fail also on that account.

[315] The EU directive states that by 2017 biofuels must reduce CO_2 emissions by 70 percent, which may reduce the demand for first-generation biofuels and may open up for second-generation fuels.

A double counting would provide an added incentive to investors in second-generation fuels that better reflects its performance in terms of CO_2 emissions. Market uncertainty remains high, however, and is magnified by the interdependency with the price of conventional fuel. Assuming that both first and second-generation transportation fuels are blended into diesel, the competitiveness of second-generation vis-à-vis first-generation will depend on the price of conventional fuel. If that price increases, first-generation biofuels gains a competitive edge simply because it, in terms of volume, replaces about twice as much diesel as the second-generation fuels from biomass (Choren, 2007b). Thus, potential investors must consider the future prices (over decades) of not only first and second-generation biofuels but also of conventional fuels. This adds uncertainty to any investment analysis.

The effectiveness criterion, thus, excludes not only TGCs and CO_2 trade but, arguably, also a general quota. At best, a double counting of second-generation transportation fuels from biomass may be expected to induce a sequential development of the three technological trajectories, starting with the lowest cost alternative.

A separate *blending quota* designed for second-generation fuels would alleviate the problem of interdependency with the price of conventional fuel and take away the market uncertainty with respect to first-generation biofuel. As and when the first larger plants are constructed, a predetermined quota could be applied. In order to stimulate a supply capacity in the Nordic countries, a unified EU separate blending quota for second-generation fuels would, of course, have to be coupled with trading opportunities, in other words an export from Sweden and Finland to other countries (as is specified in Directive 2009/28/EC). However, integrating the Nordic and German markets may lead to equity problems. As argued in Chapter III, the estimated cost levels of second-generation fuels differ a great deal, to the advantage of Swedish and Finnish suppliers. With an integration of the markets, price levels are expected to be equalised, with potentially huge excess profits gained by the Nordic suppliers.[316]

[316] A (less likely) risk is that the Nordic suppliers would expand so rapidly that they could fill the whole German quota and out-compete emerging German competitors. A low quota would, therefore, lead to market uncertainty in the sense that a supplier of a higher cost alternative would always face an uncertainty with respect to whether there will be a market or not. This may lead to a sequential development and jeopardise the effectiveness

An additional problem with a quota is the very substantial information requirements for a central planner in setting the quota, both its initial level and its escalation. Basically, today nobody can say with certainty when the first commercial plant will be operational. It is even more difficult to judge how quickly the supply capacity in the capital goods industry can grow, as it depends not only on the strategic choice of a number of capital goods firms but also on the access to specialised skills in a range of areas, including gasification and catalysis. A recurrent theme in interviews with capital goods suppliers and other firms was the lack of specialised competencies in the field.

Feed-in with cost covering payment that differs between technologies is a well proven regulatory framework to stimulate the diffusion and further development of a range of technologies in parallel, that is a feed-in tariff is expected to score high on the effectiveness criterion. Just as double counting in a quota system, a feed-in tariff may stimulate more expensive, but higher performing alternatives through setting higher prices. In principle, excess profits may be avoided by a careful price-setting routine. Such prices, which are normally set for a period of 15-20 years, would, however, need to be adjusted for fluctuating feed-stock prices.

However, there are two major problems with this instrument, at least at this stage. First, effectiveness necessitates that one tariff is set for each technological trajectory. It is, however, not possible to calculate costs with the required precision without the experience of full-sized commercial plants. Second, there is, as yet, no competition in the capital goods sector within each trajectory, which means that setting a feed-in price would involve negotiations between government and monopolistic suppliers with access to superior information. This opens up for problems with the equity criterion.

Hence, a dedicated BtL quota appears to be a more attractive option, as a price does not need to be set for 15-20 years but may evolve as experience is gained. Yet, as explained above, there are very considerable information problems for a central authority to set a quota over a longer period of time. Moreover, it remains doubtful if a promise by current

criterion. Setting a relatively high quota would reduce this risk but at the expense of high consumer costs (equity).

politicians of a quota by, say, 2020 would be enough to convince firms that a market will eventually materialise with prices that will cover costs.

In sum, none of the currently discussed policy options are a strong candidate, at least not at this stage of development of the industry. Tradable green certificates, inclusion of the transport sector in the ETS and a general biofuel quota would be expected to fail on the effectiveness criterion. Double counting second-generation fuels would, at best, lead to a sequential development of the three technological trajectories and, hence, fail on the effectiveness criterion too (but less so than the prior alternatives). If high enough, a dedicated quota for second-generation fuels would promote a broad development of gasified biomass, but setting the quota level is currently fraught with extreme difficulties. Equity issues would also arise. Finally, problems with information access (and equity issues) may rule out a feed-in law.

An option would be to implement a “bridging policy” that reduces the information needs among policymakers while taking away the market uncertainties for the first set of plants. One such alternative would be to implement plant-specific tax exemptions (increasing the price competitiveness of second-generation fuels) coupled with guaranteed market and off-take price from public sector customers, or, possibly, traders or oil companies. In effect, such a price would be a miniaturised plant specific feed-in law. With regard to relative price level vis-à-vis conventional fuel, the customer would absorb the market uncertainty, but the tax exemption would reduce the size of the potential losses. At the same time, as argued above, some of the technical risks would need to be absorbed by society at large. This temporary construction would take the capital goods industry through to the stage where the first commercial sized plants are built, reducing the technical uncertainties and completing the respective value chains.[317] It would also give the added benefit of generating a pool of experience and competencies on which a long-term policy can be based, be it a dedicated quota for second-generation fuels or a feed-in policy.

[317] This refers, in particular, to the supply of bioslurries and torrefied biomass (HT-EF trajectory), downstream in the SNG value chain, for example truck engines and infrastructure for using DME.

11.3 Concluding discussion

For close to four decades, efforts have been made to develop biomass gasification, initially aiming for oil replacement in paper and pulp mills, alternative transportation fuels and for electricity production. More recently, the focus has shifted back to the supply of second-generation transportation fuels, which are expected to become a major substitute to conventional fuels, fossil-based alternatives and first-generation biofuels, contributing to a reduction in GHG emissions while increasing security of supply.

In the EU, three main technological trajectories are explored to gasify biomass. Nine alliances of firms, institutes and universities each centre on pilot and demonstration plants in which one of these trajectories is applied to a specific context. These alliances plan to use different production processes, different feed-stocks (e.g., black liquor, straw, forest thinning, etc.), and supply different types of second-generation fuels (DME, Fischer Tropsch diesel and SNG). For these alliances, the challenge is to finish building the demonstration plants, to radically upscale these and to supply second-generation transportation fuels from the first commercial sized plants by about 2020.

It is, however, not until subsequent plants are built that second-generation transportation fuels may make significant inroads into the market. Expectations that this will take place before 2020 are probably too optimistic. As with other large-scale technological transformations, the time axis extends into multiple decades. The long-term (2030–2050) market potential for both capital goods and fuel is, however, probably very large but very uncertain. This potential rests on the ability to secure an enlarged supply of biomass, to ensure the allocation of a substantial share of it to biofuel and to reach a high efficiency in transforming that biomass to fuel. Hence, the potential market is large but uncertain and very distant.

These features meet potential investors throughout the whole value chain, from agriculture to transport equipment. Uncertainties in terms of the regulatory framework governing the outcome of investments abound. This needs to be recognised by policymakers who, in turn, must demonstrate a long-term commitment to the field by addressing the two remaining system weaknesses (specified in Chapter IX).

These weaknesses can be addressed by policy instruments that reduce the remaining technical and market uncertainties, thereby securing that industry continues to develop the technology in all its aspects.

From an investor's perspective, a commitment to second-generation biofuels involves facing a number of technical uncertainties that can only be reduced through building demonstration plants. Moving towards commercial-scale plants involves, however, a dramatic up-scaling and an increase in costs. As the Swedish case demonstrated, the sums involved are so large that current demonstration programmes, or schemes for risk absorption, need to be significantly enlarged to ensure that plants in all three trajectories—using different feed-stocks and supplying different second-generation fuels—are up-scaled. However, such large-scale schemes risk creating a phenomenon in which other technologies are crowded out.

It may well be argued that such large-scale demonstration plants should mainly be funded at the EU level, developing technology that would satisfy quotas set by the Commission and generating benefits for the whole of the EU. Indeed, as all projects progress, they will depend on inter-European alliances since no country (possibly with the exception of Germany) has firms covering the necessary knowledge for commercialising the gasification for advanced chemicals and transportation fuels. The industry is likely to evolve into a European one and not a national one. Therefore, it is unrealistic that local or national governments should fully fund costly and risky large scale demonstrations.

Demonstration programmes that absorb technical uncertainties are not sufficient for addressing the first system weakness. Market formation programmes are also critical due to large uncertainties caused by unknown future prices for conventional fuel and other substitutes. Without reducing these uncertainties and providing an income stream to investors, we cannot expect the key firms in the alliances to go ahead with the very expensive up-scaling of the technologies to commercial-scale sizes. Nor can it be expected that actors with complementary competencies and resources enter the system, reducing organisational and technical uncertainties along the entire value chain. Thus, it is pivotal that policy address the second system weakness, and thereby strengthen *market formation* through institutional alignment.

There is an abundance of different public policy instruments to form markets and assessing the usefulness of each of them requires that clear criteria are developed. The effectiveness of an instrument is assessed by its ability to meet a certain target, whereas efficiency, or cost effectiveness, refers to meeting this target at its lowest cost. As efficiency is meaningless without effectiveness, the latter takes priority. Equity is the third criterion.

Discussing the effectiveness of an instrument requires a specified goal. It was suggested that a goal for 2030 could be set at 20 percent biofuel, out of which half could be second-generation. This would amount to about 30Mtoe, involving about 150 plants. Subsequently, the market share may be increased to perhaps 25 percent. This would require not only a maximum deployment of different technologies in the Nordic countries (using local heat sinks and joint production opportunities in the paper and pulp industry) but also those higher cost alternatives under development. Reaching this goal thus necessitates the coexistence of a range of technologies with quite different cost levels. With the inherently long time axis in moving towards the first commercial-scale plants and the subsequent multiplication of these, effectiveness, therefore, *involves creating markets for all of the three trajectories* which then will develop in parallel rather than sequentially.

Most of the currently discussed policy instruments fail on this criterion. This refers to tradable green certificates, inclusion of the transport sector in the ETS and a general biofuel quota. Double counting second-generation fuels would be expected to fail on the effectiveness criterion too, but less so. A dedicated quota for second-generation fuels would, if high enough, promote a broad development of gasified biomass but setting the quota level is currently fraught with extreme difficulties in terms of information access for policymakers. Equity issues would also arise. These problems may also rule out a feed-in law.

A way forward is a "bridging policy" that takes away market uncertainties for the first plants whilst reducing the information needs among policymakers. This bridge could be built by implementing plant-specific tax exemptions coupled with a guaranteed market and off-take price. The market uncertainty is absorbed by the customer but the tax exemption would reduce the size of the potential losses. This bridge would a) ensure a market; b) demonstrate a strong commitment to the technology; c) take the capital goods industry through to the stage where the first commercial-sized plants are built, reducing the technical uncertainties and populating the respective value chains; and d) generate a pool of experience and competencies on which a long-term policy can be based. Whereas it was argued above that the EU should fund the bulk of the demonstration programmes, the tax exemptions and the guaranteed market/off-take price may be set at the national levels in order to demonstrate the commitment from local actors—including policymakers—strengthening the alliances.

Chapter XII
Contributions and implications for policymakers, system builders and future research

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In Chapter I, the purpose of this thesis was specified as to " ... *analyse the role of the system builders in the emergence of an industry with the capacity to realise the potential of gasified biomass for the production of second-generation transportation fuels and other chemicals within the European Union.*"

The analysis has focused on nine projects in four European countries—Austria, Germany, Sweden and Finland—where the main technology development within the field is currently taking place. In this thesis, the analysis has been divided into three parts and twelve chapters.

In Chapter II, the analytical framework was laid down and four research questions were formulated, addressing (1) who act as system builders; (2) the nature and extent of their transformative capacity; (3) the limits to their transformative capacity and how these can be explained; and (4) given these limits, which system weaknesses remain to be resolved by system builders and policymakers?

In Chapter III, the history of fossil and biomass gasification was outlined. Three main technological trajectories in the production of second-generation fuels and other chemicals were described, as were the characteristics of nine major projects in Europe pursued by various alliances. The methods used were described in Chapter IV which marked the end of Part I—Setting the scene.

In Part II, the four case studies—Austria (Chapter V), Germany (Chapter VI), Sweden (Chapter VII), and Finland (Chapter VIII)—were presented. For each of these, the history of biomass gasification was described along the three main technological trajectories, leading up to the current projects (as of 2009). The four research questions were answered for each country.

In Part III, "Back to the future", a cross-country analysis of the four research questions was presented (Chapter IX). Whilst the focus of the thesis has been on the system builders, the case studies made clear that also other actors and elements contributed to system dynamics. These contributions were analysed in Chapter X. In Chapter XI, policy options for addressing the remaining system weaknesses were specified.

The purpose of this final chapter of the thesis, Chapter XII, is to present the main analytical and empirical contributions, and discuss implications for system builders, policymakers as well as for future research. The chapter is divided into three sections. The first section presents analytical and empirical contributions; the second section discusses implications for system builders and policymakers; and the third section points to some implications for future research.

12.1 Analytical and empirical contributions

Schumpeter (1934), Hughes (1979), Summerton (1994) and Carlson and Jacobsson (1997) have previously described entrepreneurs, system builders and prime movers as key actors in the formation of new industries and innovation systems. On some occasions, the innovation system literature has described system builders and prime movers as a constellation of actors, networks or alliances (cf. Jacobsson and Johnson (2000)). However, following in the Schumpeterian tradition, evolutionary and innovation system literature has primarily portrayed the firm, and not the individual, as the key actor (Nelson, 1995b).

In this thesis, a systematic analysis has been undertaken, identifying a wide range of actors taking on the system building role. With research question one (RQ1, Chapter IX), it was demonstrated that such a role can be taken by a wide range of actors such as individuals, institutes, policymakers, established networks, as well as private and public firms.

In common for all these system builders is that they do act to form alliances (and networks) with other actors, along the value chain, with the required complementary resources and competencies for commercialising the knowledge field. After successfully having created such alliances (and networks), these take over the system building role, even if certain individuals may remain very influential in the networks. Hence, empirically this thesis contributes with:

a) *a systematic analysis of who act as system builders in various contexts.*

Hellsmark and Jacobsson (2009), as well as this thesis, presented an improved conceptualisation of the role of system builders in realising the potential of an emerging technological field. This was done by including Giddens' (1984a) concept of "transformative capacity" into the TIS framework, as a means of analysing the extent and limits of the system builders in creating and strengthening the embryonic structure and various functions of a TIS in a formative phase. Hence, this thesis contributes with:

b) *an improved conceptualisation of system builders for analysing the extent and limits of their transformative capacity as they act to form and strengthen the embryonic structure and functions of the TIS.*

In Chapter IX, it was argued that the transformative capacity of the system builders is conditioned but not determined by the general structure in which they are embedded. By using this general (NSI, RSI, SSI) structure (see Figure 2.1 in Chapter II), the system builders have been able to strengthen three sets of functions—"know how", "know about" and "enablers"—as well as creating or strengthening the TIS-specific structure directly. In Chapters II and IX, the "know how" and "know about" functions were identified as epistemologically distinct from each other, since strengthening these processes result in building different types of knowledge in the TIS.

The first set—the "know how" functions—is made-up of the functions *knowledge development and diffusion, entrepreneurial experimentation* and *materialisation.* The system builders strengthen these by conducting basic research, experimenting and testing new ideas, and by constructing various types of technology related structural elements such as patents, plants, components, and instruments. These elements then become part of the science and technology infrastructure of the TIS, on the basis of which further experiments and knowledge development can be made.

When the "know how" functions are strengthened, the system builders develop an embryonic industrial capacity, necessary for exploring various types of applications and feed-stocks, and moving from the construction of pilot and demonstration plants to commercial-scale facilities. However, strengthening the "know how" functions and developing an industrial capacity sufficient for finalising the formative phase, thereby beginning to realise the potential of the emerging TIS, requires that the "know about" functions, "enablers" and all of the structural elements of the TIS are also strengthened.

The second set of functions was labelled "know about" functions—*legitimation* and *direction of search.* These functions are strengthened, for example, as the system builders conduct system studies and build plants, both of which demonstrate the opportunities of the technology. More fundamentally, the system builders strengthen these functions by aligning the technology to the structure in which they are embedded, including various incumbents. Hence, strengthening these "know about" functions is essential for attracting actors and for formation of networks.

The third set of functions was called the "enabling" functions—*resource mobilisation, market formation* and *positive externalities*. The system builders were able to strengthen the enablers by a) mobilising resources from the general structure, in which they are embedded, as well as by inducing entry of firms to the TIS and creating networks (*resource mobilisation*), and b) creatively identifying market opportunities (*market formation*). In combination with positive externalities that arise from actions undertaken by the system builders themselves, as well as by other actors in the TIS, the system builders are capable of further strengthening the "know how" and "know about" functions of the TIS.

Through strengthening the functions, the system builders are able to create or strengthen the structural elements of the TIS. These may also be strengthened directly. For example, the system builders can create actors by starting new firms and technology by constructing new plants, etc.

The contributions made to system dynamics by pilot and demonstration plants were emphasised, as these are used by the system builders as their primary "tool" or instrument for aligning the technology to the interest of incumbents in the structure and to attract new actors with complementary competencies and resources, thereby creating alliances and networks. Hence, this thesis contributes by:

c) *an improved conceptualisation of how the system builders interact with the structure in which they are embedded.*

d) *illustrating how the system builders align the technology to the structure, thereby strengthening the "know about" functions, attracting actors and creating networks and alliances. The new actors, networks* and *alliances strengthen the enablers which, in turn, positively influence the "know how" functions of the TIS.*

e) *illustrating how the system builders use pilot and demonstration plants as a tool in the alignment process.*

As mentioned in Chapter II, a range of authors have argued that system weaknesses constitute a guide for policymakers who aim to stimulate innovation, the creation of new industries and economic growth (Lundvall, 1992; Lundvall and Johnson, 1994; Malerba, 1996; Smith, 1996; Carlsson and Jacobsson, 1997; Metcalfe and Georghiou, 1997; Smith, 2000b; Edquist, 2002; Metcalfe, 2004; Smits and Kuhlmann, 2004; Klein Woolthuis et al., 2005; Lundvall, 2007; Foray, 2009; Bergek et al., 2010b). However, it has also been argued that system builders may very well act upon system weaknesses in their own self-interest (Smits and Kuhlmann, 2004; Bergek et al., 2010a). The capacity of system builders to do so was also illustrated throughout Chapters V-VIII.

From a policy perspective, knowing who the system builders are and what they are **(not)** capable of is of crucial importance for two main reasons. First, this type of knowledge is necessary for enabling policymakers to set realistic targets. Second, it is necessary for policymakers to tailor appropriate and effective measures for achieving such targets, taking into account limitations in the transformative capacities of the system builders. Hence, this thesis contributes with,

f) *a rationale for identifying system builders in the formative phase of TIS.*

g) *strengthening the TIS framework with respect to its ability to aid analysts in identifying which system weakness that system builders may address themselves and those that need to be further addressed by policymakers, thereby providing*

   i. *an analytical link between the micro and macro level, which makes it possible for policymakers to set more realistic long-term goals for new technologies.*

   ii. *a general and useful method that can be used by policymakers for formulating appropriate policy interventions tailored to the needs of an emerging TIS of strategic importance.*

The innovation processes that these system builders take part in, have been described as highly contextual and path dependent (Rosenberg, 1976; Dosi, 1982; Nelson and Winter, 1982). From such a perspective, actors make decisions based on their individual contexts rather than freely from previous constraints.

In Chapter IV, it was argued that for research to matter for policymaking, context-specific analysis is pivotal, as it allows us to gain an understanding of how and why different actors decide to learn and develop a new knowledge field, as well as which uncertainties must be reduced in order for these actors to continue making choices that, over the long-term, may progress the field to complete the formative phase and shift it into a phase marked by rapid market growth.

The value of this thesis is, thus, not in making predictions about the future. Rather, it is to provide a highly context-dependent analysis on what it takes for a range of actors, from both public and private sectors within the European Union, to realise an emerging TIS with potential to contribute to abating climate change. Hence, from an empirical perspective, this thesis contributes with:

h) *a rich and contextual description of the history and development of biomass gasification in Europe starting in the 1970s in Sweden and Finland, and from the early 1990s in Austria and Germany.*

In this specific case, virtuous circles between the functions and the structure have been created. However, from the perspective of completing the formative phase and shifting the TIS into a growth phase, it was argued in Chapter IX that system builders have been limited in their capacity to strengthen the “know how” functions, which has resulted in an insufficiently strong technology and actor structure, and the current demonstration plants are, therefore, not yet in operation.

It was also argued that the system builders have been limited in their capacity to create joint political network(s), advocating alignment of institutions and technology, thereby strengthening the enabling function *market formation.*

Without such an alignment, it will be difficult to attract actors with the required complementary resources to the field and to resolve the remaining technical problems. Based on the limits of the system builders’ transformative capacity, it was thus possible to identify two main system weaknesses of the TIS:

1) *the first system weakness identified on an EU level is insufficient actor and technology structures in support of the development and diffusion of second-generation fuels.*

2) *the second system weakness identified on an EU level is the lack of joint political network(s) advocating for an alignment of institutions and technology.*

In Chapter XI, policy options for addressing these system weaknesses were outlined and it was concluded that policy needs to commit substantial resources to reduce the remaining technical uncertainties. In addition, policy must address the very large market uncertainties. If these are not addressed, actors with required complementary competencies and resources may not enter the TIS, and the system builders may not to be able to find investors willing to commit the amount of capital necessary for the construction of the first commercial-scale demonstration plants.

It was also concluded that it is too early to introduce general policy instruments for reducing market uncertainties. Instead a “bridging policy” was suggested, in which the market uncertainties are reduced for the first plants by implementing a tax exemption coupled with a guaranteed market and off-take price. Hence, in the case of biomass gasification, an empirical contribution of this thesis is:

j) identification of the main system weaknesses and an analysis of policy options addressing these weaknesses.

The focus on the extent and limits of the system builders' transformative capacity has made visible contributions to system dynamics by other actors and elements. In Chapter X, the main contributions of demonstration plants, universities, institutes, industry, and policy were specified. Apart from demonstration plants, it is of course among these actors that we find the system builders. For example, some of Germany's institutes appeared to have institutionalised the system building role acting as "catching-up learners" (cf. Dalum et al., (1992) and Lundvall and Johnson (1994)), as well as "system memory" and "node" (see VTT, Chapter VIII).

In the Finnish and German case in particular, there appears to be extensive collaborations between institutes and universities, but also strong competition over resources and contracts with industry. In these cases, the institutes seem to take on the role of conducting research on process development and hosting the required large-scale experimental science and technology infrastructure,[318] while universities appear to focus more on basic science and on educating the future human capital base. In a best case scenario, the institutes and universities should be able to find a relationship in which they strengthen, rather than cannibalise, each other.

The contributions of established industry to system dynamics is particularly important within the field of biomass gasification since these firms possess many resources, both up-stream and down-stream to gasification, that small entrepreneurial firms cannot develop. However, even if the emerging technology may provide an interesting opportunity to revitalise their current businesses (and not only a threat), encouraging them to participate and contribute to the TIS may prove very difficult. In particular, it has been possible to observe that rapidly

[318] This is, of course, something that the industry also does and on a much larger scale.

growing markets for conventional biomass CHP and coal gasification have influenced the direction of search of incumbents away from biomass gasification.

Policy can contribute to system dynamics by taking on the role of the "midwife" and re-formulating the rules of the game (Edquist, 2002). They can do so by acting upon the system weaknesses specified in this thesis, thereby reducing the structural constraints faccing the system builders. This may reduce technical and market uncertainties to an acceptable level for further firms to enter the field, thereby creating the conditions necessary for finalising the formative phase and shifting the TIS into a growth phase by 2020. Hence, this thesis contributes with:

k) a deep understanding of the interplay between various actors in the formation of a TIS.

The following chapter will summarise the main implication for system builders and policymakers.

12.2 Implications for system builders and policymakers

In this thesis, it has been illustrated that developing the necessary industrial capacity for realising the potential of second-generation fuels take decades. Even if actors involved can draw upon a 200 years of experience in fossil gasification, as well as on different experiments with biomass gasification since the 1970s, industry has not developed the necessary capacity for completing the formative phase, shifting it into a growth phase. Hence, the first implication for policy is that:

a) it takes many decades to develop technology options, such as the production of second-generation fuels from biomass, to abate climate change.

For putting various technology options on the "shelf" (Sandén and Azar, 2005), an industrial capacity for these must develop through the accumulation of knowledge over an extended period of time. It is, therefore, essential that industry has the opportunity to experiment with various types of applications, feed-stock and on different scales over long periods of time.

The construction of pilot-, demonstration- and commercial-scale plants is an essential part of such experiments. The importance of demonstration plants that carry their own operating costs for less advanced applications, while experiments are made on more advanced, was emphasised as these enable actors to quickly explore new ideas and test various types of concepts. These experiments, in combination with the construction of less advanced (but still commercial-scale) plants are necessary for increasing the level of knowledge to an expert level and for gaining commercial experience with novel technologies.

When continuous experimentation is undertaken, a science and technology infrastructure is created. Based on such an infrastructure, further experiments can be conducted and the knowledge field can advance in new and on beforehand unknown directions. Hence, for policy to support the development of an industrial capacity, it must support:

b) *many types of experiments, including a wide range of applications and configurations at pilot, demonstration and commercial scales over an extended period of time.*

In Chapter XI, it was argued that it is necessary to support experiments with all three technological trajectories under development. The various trajectories do not represent conventional "competing designs" that fully substitute for one another (Utterback, 1994), and there are still technical uncertainties that may prove too difficult to solve along their entire value chains. Prioritising one trajectory over another is, therefore, at this stage not advisable and may seriously hamper the possibility to realise the potential of producing second-generation fuels from biomass. Hence, it is concluded that it will be necessary for policy to:

c) support the demonstration of all three trajectories, including all complementary knowledge fields along the entire value chain.

Already in Chapter III, it was emphasised that although most of the bits and pieces of knowledge necessary for creating complete systems for turning biomass into usable transportation fuels already exists today, these have never before been combined into complete value chains. As these existing knowledge fields have developed independently of each other—by firms with no tradition of cooperating—these knowledge fields must be adapted to each other and new knowledge concerning their integration must be developed. In addition, new and complementary products, services and distribution channels may have to be developed.

For succeeding with the demonstration plants, system builders depend on the participation of incumbent actors with access to complementary resources and competencies. For example, to develop DME or SNG as an alternative fuel, new engines and new fuel infrastructures have to be developed. For actors interested in FT diesel, only two catalyst developers have commercial plants operating, and they do not participate in the current technology development. Hence, for developing an industrial capacity and successfully demonstrating the technology:

d) *system builders are dependent on the creation of strong alliances with incumbents with complementary resources and competencies along the entire value chains.*

For the system builders to be able to create such alliances with incumbents, both nationally and internationally, they depend on a being embedded in a rich and heterogeneous structure. Such a structure consists of a wide range of technology specific and neutral instruments, incumbent industries and networks from which they can draw resources as well as create initial markets.[319]

In Chapter X, it was argued that the primary role of policy is to tend to the creation and maintenance of such a structure. Policymakers then take on the role of a "midwife" (Edquist, 2002) in the creation of new industries without actually trying to "pick" winners (Carlsson and Jacobsson, 1997; Lundvall, 2007). However, as the example of Sweden illustrates (Chapter VII), without a rich and heterogeneous structure, policymakers with an interest in developing the knowledge field were forced into a policy of picking winners.

Creating such structures implies that policymakers at EU, national and regional levels shift from having a short-term focus on succeeding with individual projects to focusing on

[319] Since markets in the emerging TIS may not generate any substantial income streams for a decade or so. As mentioned above, the institutional framework must, therefore, provide strong incentives for incumbents to allocate resources from existing and growing markets (such as biomass combustion or coal gasification) to develop the emerging TIS.

strengthening emerging actor and technology structures. In Chapters VII and X, it was argued that the primary focus of policy when funding research, development, pilot and demonstration projects should be to identify:

i. what type of science and technology infrastructure is created. Is it useful beyond a single experiment or demonstration and, if so, who can continue to learn from it?

ii. who has the ability to appropriate the benefits of the knowledge development, even if the project itself fails?

A key implication for policy is that it should:

e) ***not** focus on succeeding with individual projects, since failure of such projects is more certain then their success. Instead it should,*

f) *tend to the creation of a rich and heterogeneous structure from which both new system builders and strong industrial alliances can emerge.*

For completing the formative phase and shifting the TIS into a growth phase, system builders and policymakers must, as mentioned above, address the two main system weaknesses by reducing existing technical and market uncertainties. These uncertainties discourage actors with complementary competencies and resources from entering the TIS, and investors from committing substantial resources for scaling-up the technology to a commercial size (see Chapters IX and XI).[320] For strengthening market formation and thereby reducing market uncertainties, an institutional alignment is necessary.

However, fierce competition between system builders causes conflicts and makes it difficult to form political networks and speak with a common voice for an alignment of institutions. Hence, a key task for system builders is to:

g) *overcome internal conflicts, create political networks and advocate for an aligned institutional framework that would benefit the development of a wide range of solutions for the production of second-generation fuels.*

[320] The two system weaknesses were discussed in the previous subsection and will not be repeated here.

Meanwhile, policy will need to take responsibility for reducing technical and market uncertainties. The implications for policy were specified in Chapter XI, where it was argued that completing the formative phase of the TIS would take at least an additional 10 years and involve investments in the range of €5 billion to get all trajectories up and running.[321]

Even if only 20 percent is covered through government budgets, €1 billion is still a substantial investment in demonstration programmes, which risk crowding out investments in other technological fields. As illustrated with the examples of BIGCC in Värnamo and the current example of Choren, making demonstration plants operational takes considerably longer than most system builders and investors willingly admit. It is, therefore, unlikely that 10 years will be sufficient to complete the formative phase. Hence, for policy this implies that they should:

h) *focus on providing substantial resources and "patient capital" that allows for the remaining technical uncertainties to be reduced, at best, in the following decade.*

From an investor's perspective, the technical risks of pursuing commercial-scale gasification projects may appear great. Nevertheless, these are small in relation to the market risk of investing in full-scale plants. Depending on the future price of biomass (which is very uncertain), the production cost of second-generation fuels in a plant with a capacity of approximately 0.2Mtoe of fuels per year will be in the range of $80-165 per barrel of oil equivalent (Chapter III).

For reducing market risk for investors, the European Commission has decided that *" ... contribution made by biofuels produced from waste, residues, non food cellulosic material, and lingo-cellulosic material shall be considered twice that made by other biofuels ... "* to the 10 percent target (EC, 2009a, Article 21:2).

Even if the new directive provides some additional incentives for investors, it was argued in Chapter XI that these will not be sufficient for reducing the market risk in relation to fossil

[321] This sum would include the construction of the pre-commercial demonstrations and all of the nine commercial-scale demonstration plants described in Table 11.1, Chapter XI. It excludes costs of forming markets.

fuels and first-generation biofuels. Hence, in addition to reducing the technical risks policy should:

i) focus on providing incentives that reduce the market risk to acceptable levels for investors.

In Chapter XI, two main policy alternatives for reducing the market risk were examined—a separate quota for second-generation fuels and a feed-in law. However, none of the alternatives came out as a strong candidate, as it was argued to be too early for introducing general policy instruments. Instead it was suggested that a “bridging policy” could be introduced, implementing tax exemption for the first commercial-sized plants coupled with a guaranteed market and off-take price granted by public sector customers with an interest in securing supplies of renewable fuels at a fixed price.

12.3 Implications for future research

Based on the results presented in this thesis, it is suggested that future research may take two main directions.

First, in the creation of a new TIS, various elements contribute to system dynamics without necessarily taking on a system building role. In Chapter X, contributions to system dynamics were elaborated on from the perspectives of demonstration plants, institutes, universities, industries, and policymakers. Each of these can contribute to system dynamics in many different ways, and how they contribute differ between different contexts and situations.

Nevertheless, it may be possible to define a fixed set of roles that different actors may take in the formation of a TIS but where one actor can take more than one role. Each of these roles should be defined by what type of structure and functions that are directly built, or strengthened, by the actor who takes on the specific role.

Based on such taxonomy, it should be possible to visualise the different roles various actors take in a given TIS, how they compete or complement each other in different contexts (if some roles are not taken at all), and if some are taken by one actor in one context but not in another. Such a conceptualisation should be useful for analysing the interaction between various actors, and how these actors contribute to the development of the TIS in the various phases. In addition, it should be possible to use the taxonomy when assessing the "usefulness" of, for example, academia or institutes. Such assessments are of interest to policymakers when spending money on various research and development programmes (Perez Vico, 2010).

If one can, in a systematic way, categorise what types of roles that, say, academia may take in relation to other actors, it should improve the validity of such assessments. For example, there is little value in assessing the "usefulness" of an academic department based on its ability to start firms and conduct research on process development, if that is not the role it has taken in a given TIS. That is to say that using the same criteria for assessing the work undertaken by Professor Hofbauer at TU Vienna in Austria and Professor Huppa at Åbo Akedemi in Finland, or for the institute VTT in Finland compared to the institutes in Germany (FZK, ZSW and CUTEC), would be gravely misleading, since the contexts in which they operate are very different from each other (see Chapter X).

Hence, once it is established what type of role a specific actor takes in the system, it is easier to determine what variables one should use to measure how well this actor performs. Obviously, such an assessment should not only be based on a set of end-variables—such as number of patents, publications or firms started—but also on a qualitative assessment of how well actors make use of the structure, in which they are embedded to create and strengthen the various structural elements and functions associated with that specific role. The first step towards creating such a taxonomy has already been taken in a Master's thesis (Andersson and Vargas, 2010), but it should be further developed.

Second, it would be interesting to further explore how policy can prioritise between various emerging TIS. From an evolutionary perspective, it has been argued that the main role of policy is to maintain and stimulate the creation of variety. This is of particular importance in a time of climate change, since accomplishing a shift towards a CO_2-neutral society requires the development of an industrial capacity for a wide range of technologies, and that these are diffused on a large-scale within a relatively short time frame.

However, as emphasised in Chapter XI, off-loading the technical and market risk for investors in technologies such as biomass gasification and taking these beyond the formative phase will require substantial funding from the government. Similar and large-scale investments are likely to be required in other areas such as off-shore wind power, concentrated solar power, carbon capture and storage, but also in high speed railways, electrification of vehicles, etc.

All governments taking climate change seriously face an extremely challenging predicament: they must invest substantial sums in one area and risk crowding out technologies in others. At the same time, there are no guarantees that investments in immature technologies will be successful. A central question to further explore is, therefore, on which base priorities should be made for government investments that can result in both CO_2 reductions and the creation of an industrial capacity necessary for developing and diffusing these technologies on a large-scale.

From this a perspective, to give priority to technologies with the lowest CO_2 abatement costs is not necessarily a very good idea. If technologies with the lowest cost are given a high priority by introducing "technology neutral" incentives such as green certificates, it will be difficult for the immature alternatives, with a high potential in the long-term, to complete the formative phase and for an industrial capacity to develop (Bergek and Jacobsson, 2010). The alternative is to pursue a long-term industrial policy with technology-specific elements.

However, with such a policy the risk of failure is always present and such failures must be planned for. From a national policy perspective, investing in projects that "fail" should at least result in the creation of a science and technology infrastructure that can be used for further experiments. It is, therefore, necessary that investments made should benefit a primarily national-based actor structure that can learn from such failures.

Since the actor (industry) structure is different from one country to another, each country will have unevenly distributed opportunities to appropriate on investments made to realise the potential of various technical options. This means that current industry structure must be allowed to influence the priorities made between various emerging TIS. However, this path dependency should not be construed as inertia that prevents the exploration and development of new opportunities. Hence, partial answers to the question have already been provided in this thesis, but a framework that would allow policymakers to give priority to one area over another could be further developed.

List of Abbreviations

AER	Absorption enhanced reforming
BFB	Bubbling fluidised bed
BioSNG	Synthetic natural gas from biomass
BLG	Black liquor gasification
Boe	Barrels of oil equivalent
BtL	Biomass-to-liquid
CCS	Carbon capture and storage
CFB	Circulating fluidised bed
CtL	Coal-to-liquid
de	diesel equivalent
DME	Dimethyl ether
EC	European Commission
EEG	Erneubare-Energien-Gesetz
EF	Entrained flow
el	electricity
FB	Fluidised bed
FICFB	Fast Internal Circulating Fluidised Bed
FT	Fischer–Tropsch
GHG	Green house gases

GtL	Gas-to-liquid
HT	High temperature
IGCC	Integrated gasification combined cycle
LT	Low temperature
NSI	National systems of innovation
RDF	Refuse-derived fuel
RSI	Regional systems of innovation
SNG	Synthetic natural gas from fossil resources
SRC	Short rotation coppice
SSI	Sectoral systems of innovations
t/d	Tonnes per day
tbd	Tonnes of black liquor solids per day
th	thermal
TIS	Technological innovation systems
Toe	Tonnes of oil equivalent

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CHALMERS UNIVERSITY OF TECHNOLOGY
SE-412 96 Gothenburg, Sweden
Telephone: +46-(0)31 772 10 00
www.chalmers.se