CHALMERS

# Resource mobilisation for energy system transformation

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THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

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*Homo sapiens står inför problem av*
*planetär omfattning. De kan lösas om vi*
*förmår tillverka ett ”vi” som består av*
*hela mänskligheten. De är inte ett större*
*steg än våra tidigare. Världen behöver*
*tas på allvar. Men man behöver nog*
*inte vara så himla rädd.*

Skymningssång i Kalahari, Lasse Berg

## Abstract

A transition to a sustainable path of development will require that fossil fuels are replaced with renewable energy sources and involve, therefore, a large-scale transformation of the energy system. In the EU, offshore wind power and biorefineries have the potential to play an important role in this transformation. This thesis focuses on development and, particularly, diffusion of these technologies and the associated crucial mobilisation of resources. First, the formation of competences is analysed, with focus on the need for engineering competences in the offshore wind sector. Second, an analysis is made of an incumbent industry that is in control of strategic raw material, competences and technical systems and which, therefore, can hinder or drive the development of technology. The incumbent industry in question is the Swedish pulp and paper industry and the focus is on the adoption of biorefinery options. The analytical framework used is constructed by combining literature on innovations systems, transition management and strategic management. This combination contributes to a better understanding of the interactions between different system levels.

The analysis of the human capital required to realize an expansion of offshore wind power shows that there is a need for both deep competences and new types of integrated competences. By 2020, the number of additional engineers needed in the wind power value chain may easily go beyond 10 000. The demand for competence has implications for the universities, which need to expand the number and types of educational programmes. This up-scaling of university programmes will require that the associated teaching staffs are enlarged. It may also require support for a European portfolio of specialized courses that are made available to students from different universities.

The analysis of the pulp and paper industry describes how the industry has started to change its attitude towards development of biorefinery technologies due to pressure from several changes at a societal level. This far, the industry’s reaction to these changes has been modest and is characterized by incremental change and extended vertical integration. However, development along two new technological trajectories (including development of gasification and separation/refining technologies, respectively) can be identified. The firms’ different reactions to pressure can be explained by their different prerequisites regarding resources, skills, position and experience. These reactions can be seen as an initial phase of a regime fragmentation and could constitute a starting point for a transition.

*Keywords: Resource mobilisation, Energy system transformation, Offshore wind power, Biorefineries, Incumbent firms, Competences*

# List of included papers

## *Appended papers*

*Paper I*
Jacobsson and Karltorp (2011), *Formation of competences to realise the potential of offshore wind power in the European Union*
Submitted to Scientific Journal

*Paper II*
Karltorp and Sandén (2011), *Diverging trajectories in the Swedish pulp and paper industry – initiating a regime shift*
To be submitted to Scientific Journal

In Paper I the work of data collection and writing has been equally shared between Staffan Jacobsson and Kersti Karltorp. In Paper II data collection was done by Kersti Karltorp, while the article was written together with Björn Sandén.

## *Other publications*

Johansson. D, M. Johansson, K. Karltorp, H. Ljungstedt, J. Schwabecker (2009), *Pathways for Increased Use and Refining of Biomass in Swedish Energy-Intensive Industry*, ISSN 1403-8307, Energy Systems Programme, Linköping University, 2009.

Johansson. D, M. Johansson, K. Karltorp, H. Ljungstedt (2011), *Options for Increased Use and Refining of Biomass: the Case of Energy-intensive Industry in Sweden*, Conference paper at the World Renewable Energy Congress, Linköping, Sweden, 9-13 May 2011

Karltorp and Sandén (2011), *Policy intervention and technical change in mature industry: The Swedish pulp and paper industry and the biorefinery*, Conference paper at the World Renewable Energy Congress, Linköping, Sweden, 9-13 May 2011

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# 1 Introduction

To change our society's path of development in a sustainable direction, which minimizes environmental impact and reduces dependence on finite resources, is an enormous challenge. This includes a substantial shift from fossil to renewable sources for energy and materials, which will involve radical change in many socio-technical systems. In particular, the energy system needs to go through a large-scale transformation process where carbon-based technologies are replaced by alternatives using renewable energy sources. In Europe, technologies utilising biomass and wind resources have the potential to contribute substantially to this process. Biomass can be converted into energy and material and can have an important role in the future European energy system. One estimate claims that in 2030, close to 300 TWh electricity can be produced from biomass, but biomass can also be used for other energy products such as heat and biofuels (IEA 2010). Conversion of biomass is linked to the pulp and paper industry, since this industry is in control of a large share of the biomass flow from forests and has extensive knowledge of biomass conversion and technical systems to which some of these technologies could be integrated. A pulp and paper mill that converts biomass to chemicals, materials and energy together with, or instead of, conventional fibres for paper products is referred to as a biorefinery (Larsson and Ståhl 2009). For wind power, a scenario by the European Wind Energy Association (EWEA) estimates that the wind power supply may exceed 1000 TWh by 2030 (EWEA 2009b). Almost half of this potential is found in unexploited sites offshore.

## *1.1 Scope and aim*

The process of diffusion of technology can be described in terms of an initial development phase followed by take-off, a growth phase and a saturation phase. Much of the previous research on radical technical change in the energy sector has focused on the phase of development and early diffusion of energy technologies (e.g. Bergek et al. 2008b; Meijer 2008; Hellsmark 2010; Suurs et al. 2010). In this phase, e.g. high cost, technical challenges, lack of knowledge and legitimacy can hinder the development of technology. This thesis focuses on the take-off and growth phase, in which the technology diffuses on a larger scale, and the type of obstacles that may hinder this development (Figure 1). The technologies of interest in this thesis, offshore wind power and biorefineries, are in a development phase, but in order to contribute to a transformation of the energy system a rapid and substantial diffusion of these technologies is necessary. Mobilisation of resources is crucial to overcome obstacles in all phases, but the scale of resource mobilisation needed increases as the technologies diffuse more widely. Resources that need to be mobilised to support the diffusion of technology are e.g. human capital, financial capital and other assets such as infrastructure, services and raw material (Bergek et al. 2008a).

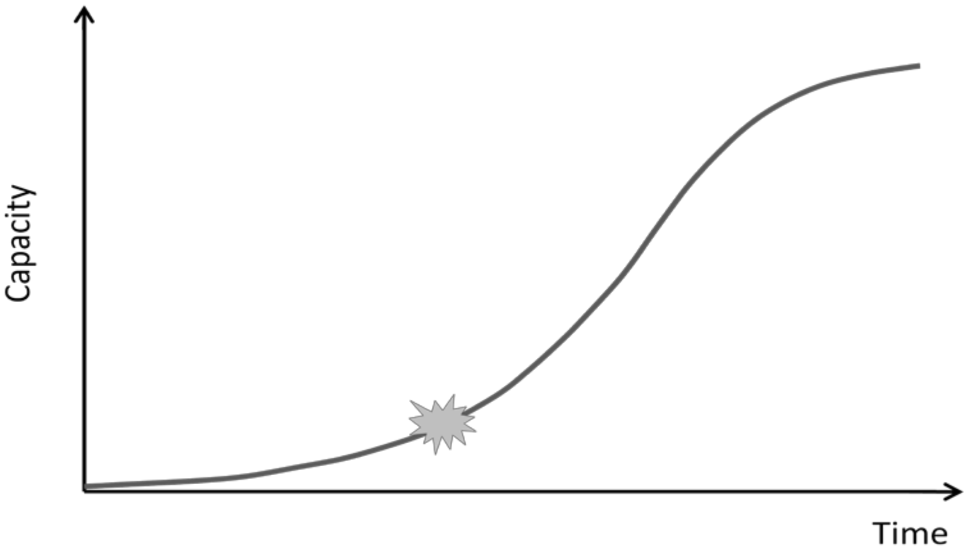

**Figure 1.** The process of diffusion of technology can be described in terms of an initial development phase followed by take-off, a growth phase and a saturation phase. The scope of this thesis is the take-off (indicated by the star) and the growth phase and the resource mobilisation needed to achieve substantial growth in installed capacity of the studied technologies.

This thesis examines resource mobilisation for development and diffusion of offshore wind energy and biorefinery technologies. The scope is limited to one analysis of resource mobilisation for each technology. First, the formation of competences is analysed, with focus on the need for engineering competences in the emerging offshore wind sector. This is analysed in Paper I. Second, an incumbent industry that is in control of a strategic raw material, competence and technical systems and which, therefore, can hinder or drive the development of technology is analysed. The second analysis is illustrated with the case of the transformation process in the Swedish pulp and paper industry, in particular the adoption of biorefinery options. This is analysed in Paper II.

## *1.2 Methodology*

Data collection for the studies included in this thesis has been conducted through two parallel interview studies during 2009–2010. Semi-structured interview guides were used, which gave room for discussion. For Paper I, twenty-one interviews were made with representatives from the wind power industry, universities and research institutes in Denmark, Germany, Sweden and the Netherlands, although the bulk of the interviews were made in Germany and Denmark as they house most of the wind turbine industry. The analysis is thus restricted to European offshore wind energy. The interviewees include managers in charge of product development in the turbine manufacturers and managers of the offshore market segment in the utilities. In universities and institutes, they include professors and heads of institutes. For Paper II, thirteen interviews were made with representatives from the Swedish pulp and paper industry, research companies and universities. The interviewees were technical directors or senior managers with experience from strategic technical development at seven Swedish pulp and paper firms, professors at universities and managers at research companies. In addition, the studies have been informed by literature and statistics as well as attendance at conferences.[1]

The representatives from the wind energy industry informed us about the technical challenges, the number of engineers presently working in the firms, and factors that influence the future need for engineers (types and numbers). For calculations of the number of engineers needed to realize the potential of offshore wind energy, a scenario was chosen for estimates of future installations (see Paper I for more details on the method used for these calculations). The interviewees from the pulp and paper industry informed us about how these actors have experienced changes in society during the last decade and how they have reacted to these changes, specifically if they have been motivated to develop new technological options. All interviewees were given the opportunity to comment on a draft of the articles, and eight for Paper I and five for Paper II, respectively, read and commented on the papers.

The next section describes the challenge of transforming the energy system that lies ahead of us, and the potential role of biomass and wind power in this transformation. Section 3 presents the theoretical framework for the thesis, and section 4 the results from the two included papers. The main conclusions are summarised in section 5, and ideas for further research are given in the final section.

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[1] For example, First European Conference on Sustainability Transition/Amsterdam 2009, World Bioenergy – Clean Vehicles & Fuels/Stockholm 2009, CEPI annual conference 2009/Brussels 2009, Wind2010/Gothenburg 2010, EWEA annual conference 2011/Brussels 2011.

# 2 The challenge of transforming the energy system

The organisation of human societies has gone through some dramatic and large-scale transitions throughout our history. The Neolithic revolution[2] is often mentioned as the first. The second great transition in human history involved the exploitation of non-renewable fossil-based energy resources, a large increase in energy consumption, industrialization and mass consumption (Ponting 2007). As a result of the increasing use of energy, mainly based on fossil fuels, our society is today causing severe environmental impact, e.g. climate change. Thus, a transformation of the energy system is urgently needed to contribute to a transition along a sustainable path of development.

In this section, the challenge of transforming the energy system is outlined. As the thesis is limited in scope to the EU 27, actions to meet this challenge within the EU are briefly presented. Given that the thesis focus on technologies utilising wind and biomass resources, estimates of the future role of these resources within the EU are given. The section ends with a brief overview of technologies for conversion of these resources.

## *2.1 Replacing fossil fuel – a global energy challenge*

The global energy supply is presently dominated by fossil fuel. Oil, coal and natural gas represented 81 per cent of the global energy supply in 2008, whereas only thirteen per cent came from renewable sources and six per cent from nuclear power (IEA 2010). In addition, large sources of fossil fuels, e.g. coal, natural gas, tar sand and oil shale, are still being developed, which provides an opportunity for continuous use of these sources (Johnsson 2011). Thus, substitution of fossil fuels is a demanding task due to their wide-spread use and the large unexploited reserves that still remain.

This task will be even more difficult as the demand for energy increases due to population growth and as living standards raise. The prospect for the world population is 8.3 billion in 2030 (UNPD 2011). This can be compared with the radical growth of global population in the last century, from 1.6 billion in 1900 to 6.1 billion in 2000 (Smil 2003). In the same time period, there has been an even more extensive increase in the consumption of fossil sources; from about 22 to 320 EJ per year (Smil 2003). This implies that while the population almost quadrupled, the energy consumption raised nearly fifteen fold. This is a result of more energy per capita being used as the living standard is raised. There are still large variations in the amount of energy used in different regions. For example, in 2008 the average energy use was six MWh per capita in India and in Africa almost eight MWh per capita, while the EU used on average 41 MWh and the United States 87 MWh (Swedish Energy Agency 2010). The energy consumption is expected to increase in regions with low energy consumption. In fact, non-OECD countries are expected to account for more than 90

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[2] I.e. the combined effect of transition to agriculture, settled societies, development of craft specialisation and rise of dominant religions and political groups can be seen as the first great transition (Ponting 2007).

per cent of the increase in energy demand in the coming decades as a result of accelerating growth of economic activity, industrial production, population and urbanisation (IEA 2010).

The International Energy Agency (IEA) estimates that the global primary energy demand will increase from 143 PWh[3] in 2008 to almost 200 PWh in 2030, if the path of development is decided by current policies (IEA 2010). Lower consumption in 2030 is reached if policies are set to limit emissions of greenhouse gases to 450 ppm of $CO_2$ equivalents, making the energy system consistent with a $2^{o}$ C target.[4] Such a '450 ppm scenario' could imply a global primary energy demand of 170 PWh per year in 2030 and that the power sector is largely decarbonised, particularly in developed countries (IEA 2010). In another scenario, made by Greenpeace, a more rapid transformation of the energy system is assumed and the estimate of the global primary energy demand is as low as 139 PWh per year in 2030 (Greenpeace and EREC 2010). To achieve this, it is assumed that the economic lifetime of coal power plants is reduced[5] and that an increased growth rate for renewable energy sources will fill the gap. Common to all scenarios is that a large-scale and rapid expansion of renewable energy sources in developed countries, like the EU's member states, is essential for overcoming the energy challenge.

## *2.2 EU's actions to meet the energy challenge*

The EU has set targets for the transformation of the energy system until 2020 and binding legislation in order to implement these targets. By 2020, the primary energy use should be reduced by 20 per cent compared to projected levels through energy efficiency measures (European Parliament and Council 2009). The building sector shows a great potential for increased energy efficiency, as a rise in energy efficiency of around 30 per cent is assumed to be cost-effective. These measures include, for example, retrofitted wall and roof insulation in residential buildings and improved energy management systems in commercial buildings. Potentials for increased energy efficiency of around 25 per cent are also identified within the industry and transport sectors respectively (European Commission 2006).

Another target concerns the share of renewable energy sources in the EU's energy mix. For 2020, this target is set to 20 per cent, which implies more than a doubling from the 9.2 per cent in 2006 (European Commission 2010).[6] Renewable energy sources can be used for generation of electricity, heat and transport fuel. IEA (2010) estimates (in the 450 ppm scenario) that the primary energy from renewable sources in Europe can increase from eight

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[3] This is nearly a doubling since 1980 when the energy demand was 84 PWh (IEA 2010).

[4] This scenario assumes that policies are introduced to limit the atmospheric concentration of greenhouse gases at 450 ppm of $CO_2$ equivalents. This level would give a reasonable chance to limit the increase in global average temperature to $2^{o}$ C and prevent dangerous interference with the climate system. This limit is also the goal set in the Copenhagen Accord, at the UN Framework Convention on Climate Change conference in December 2009.

[5] The life time is reduced from 40 to 20 years.

[6] For the transport sector the EU has a specific target of 10 per cent renewable energy sources (European Parliament and Council 2009).

per cent in 2008 to 25 per cent in 2030. Two sources of renewable energy of great importance for the EU are wind and biomass. Wind offers the possibility to produce large amounts of electricity, with low emissions of $CO_2$.[7] Biomass can be used for a wide range of energy-related applications, including generation of electricity, heat generation and production of biofuels, with low emissions of greenhouse gases. Furthermore, biomass can also be used for production of materials that can replace materials based on fossil fuels.

## *2.3 The role of wind power and bioenergy in EU*

This section presents some estimates of what role wind and biomass sources can have in the future energy system in the EU, in 2030. The analysis in the two papers included in the thesis is narrowed down further to offshore wind power and to alternative technologies for biomass conversion in a pulp mill. These technological fields are presented in sections, 2.4 and 2.5 respectively.

Wind power installations in Europe (in absolute numbers) increased quite slowly during the 1980s and early 1990s, but have then grown extensively and in the early 2000s the first offshore projects were launched. In the EU, wind turbines generated 119 TWh in 2008, equivalent to 3.5 per cent of the electricity supply (Eurostat 2011b). In 2009, 10.2 GW wind power capacity was installed in EU, representing 39 per cent of the total capacity that was installed that year (EWEA 2010c). Indeed, in terms of peak power capacity more wind power than any other electricity-generating capacity was installed. Overall, from 1998 to 2008 the amount of electricity generated from wind power in EU 27 has increased with on average 27 per cent per year (Eurostat 2011a). Germany and Spain are the EU countries with the largest installed capacity, with 34 per cent and 26 per cent[8] respectively (EWEA 2010c). In the offshore wind power market, the countries around the North Sea dominate; the UK represents 43 per cent of total installed capacity, Denmark 31 per cent, the Netherlands twelve per cent and Sweden eight per cent (EWEA 2010a).

During the last decade, installations of wind power have exceeded the target for EU several times, which has lead to frequent updates of these.[9] In 2009, the targets for 2030 from the EWEA (400GW), the European Commission (146 GW) and the IEA (232 GW) differed greatly (EWEA 2009b). The estimate by EWEA is based on analysis of the wind energy markets in the member states. It is also the scenario with the highest estimate of installations, which is promising since previous estimates have been overly cautious. According to this scenario, wind power will generate 580 TWh in 2020 and 1 150 TWh by 2030, leading to a share of wind power in electricity consumption of about 30 per cent in 2030 (EWEA 2009b).

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[7] EWEA (2009b) estimated that in 2008, 91 Mt $CO_2$ emissions was avoided in Europe as a result of wind power installations. This can be compared with the overall Kyoto reduction target in the EU- 25 (excluding Malta and Cyprus which are not included in this target) of 450 MT $CO_2$ equivalents or 7.8 per cent for 2012.

[8] In 2009 the cumulative capacity was 25.8 GW in Germany and 19.1GW in Spain (EWEA 2010b).

[9] For an overview of this development see EWEA (2009b, p.31).

Investment in onshore wind power is projected to reach a peak in 2020 whereas investment in offshore wind power is expected to continue to rise over the next twenty years (Figure 2). By 2027, the annual installed capacity of offshore turbines supersedes that of onshore in Europe,[10] and by 2030 the stock of offshore wind turbines may generate 560 TWh[11], nearly as much as the estimated 590 TWh from onshore plants (EWEA 2009b). This would, indeed, constitute a significant contribution to the EU's efforts to decarbonise the power sector and increase the share of renewable energy sources.

Conventional bioenergy, i.e. charcoal, wood and manure for cooking, heating and lighting, has been used for a long time. Currently modern bioenergy use, such as electricity generation, heat generation (for industrial purposes and district heating) and production of transport fuels, is increasing rapidly as a reaction to various policies (Berndes 2011). In the EU, biomass and waste contributed six per cent of the primary energy demand in 2008 (IEA 2010). Looking more into details of how much bioenergy that was used in different sectors: three per cent of transport fuels were biofuels and seven per cent of the energy use in the building and industry sectors, respectively, was based on biomass and waste (IEA 2010). There are large regional variations in supply and demand for bioenergy, e.g. Sweden and Finland have the largest annual wood removals in EU, followed by the Baltic countries (Berndes 2011). In Sweden, the use of biomass for energy has more than tripled since the 1970s and the biomass share of primary energy has increased from nine per cent in 1970 to 23 per cent in 2010 (Swedish Energy Agency 2010; Swedish Energy Agency 2011).

If conflicts between bioenergy and food production are to be avoided and if a positive overall environmental impact is to be ensured, bioenergy options need to be developed in a careful manner (Bauen et al. 2009; Berndes et al. 2010). Still, there is a large potential for bioenergy production. How large this potential is depends on a variety of factors, e.g. increase in productivity in food and feed production. From a biophysical perspective, it is estimated that a large proportion of Europe's[12] agricultural land (27 – 32 per cent of cultivation land and nearly 26 per cent of pasture land[13]) could be used for biomass production in 2030 (Berndes 2011). Besides agricultural resources, biomass can be supplied from forest resources. De Wit and Faaij (2010) estimate that the total the amount of primary energy from biomass in Europe could be between 2 200 and 6 800 TWh annually (de Wit and Faaij 2010). However, much of this will be lost in the process of transforming primary energy to final energy products.

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[10] 12.5 GW, up from 0.6 GW in 2009, see EWEA (2010b).

[11] It seems that the European Commission is also updating in their view to a higher estimate for the offshore sector of 560 TWh in 2030 (European Commission 2008).

[12] EU 27 and Ukraine.

[13] 27-33 per cent equals 44-53 million hectares and 26 per cent equals 20 million hectares.

There are many technologies that can be used for converting biomass resources into final energy products, such as electricity, heat and fuels, and the amount of final energy produced varies with the technological alternatives. Scenarios can be used to illustrate the overall amount of energy that could be generated from biomass in the future European energy system. In the scenario by Greenpeace (presented above) OECD Europe has nine per cent biofuels in the transport sector, in 2030. Nine per cent of the energy in the industry sector comes from bioenergy and waste, and nine per cent of the energy in other sectors comes from bioenergy (Greenpeace and EREC 2010). Another estimate is given by IEA's 450 ppm scenario (also presented above) where it is estimated that, in 2030, biomass and waste can contribute to 268 TWh, equal to seven per cent of the electricity generation in EU (IEA 2010). To compare the role of biomass with that of wind power, the estimates of power generation from these to sources are given in Table 1.

**Table 1** Estimates for electricity generation from wind and biomass in EU, 2030, based on EWEA (2009b) and the 450 ppm scenario by IEA (2010). The total electricity generation in EU 2030 is based on IEA's 450 ppm scenario (3706 TWh). Note that biomass can also be used for biofuels and heat generation.

| | Onshore wind power | Offshore wind power | Biomass and waste |
|---|---|---|---|
| Power generation (TWh) | 590 | 560 | 268 |
| Installed capacity (GW) | 250 | 150 | 45 |
| Share of electricity generation (%) | 16 | 15 | 7 |

## 2.4 Offshore wind power

Paper I in this thesis focuses on the development of offshore wind power in the North Sea. Wind power technology for onshore application is a well-proven technology, supplied by a global capital goods industry equipped with substantial resources. The offshore market is now emerging as a distinct segment and it is expected to take off in the next decade (EWEA 2009a). The offshore wind power segment has features that differ greatly from the onshore segment. Offshore wind power technology builds upon onshore wind power technology, but needs further development to be adjusted to the harsh environment at sea with an exposure of water, wind, salt and sun. Additionally, the expansion of offshore wind power requires transmission capacity to offshore sites, as well as an associated integration of offshore wind capacity into the European grid system. These aspects make the cost for installation higher, and it is therefore reasonable to develop larger turbines for offshore, which many manufacturers do. As transportation of components, such as nacelles and blades, is very difficult due to their size, manufacturing facilities need to be set up in harbours and specialised vessels are also needed to ship and install the turbines at sea. In total, this makes the development of an offshore wind power plant a very sizable project; the investment might cost 1 billion Euros or more (Giese 2010). This means that the customers are the larger utilities and not individual farmers or cooperatives, which have been a large customer group for onshore wind power plants.

## *2.5 Biorefineries*

Paper II in this thesis focuses on the development of biorefineries within the Swedish pulp and paper industry. The term biorefinery refers to a pulp mill in which one or more technologies are implemented in order to use the incoming biomass efficiently to produce chemicals or materials and energy, simultaneously with or instead of conventional fibres for paper products (Larsson and Ståhl 2009). Thus, the biorefinery concept is analogous to an oil refinery, which processes petroleum and crude oil to make a range of fossil-based products. The development of technologies that can be integrated in a biorefinery has been going on for decades (Sandén and Jonasson 2005; Hellsmark 2010). These technologies can be divided into two categories: gasification technologies and technologies for separation and refining.

Gasification is often called a platform technology since it can be based on different raw materials, e. g. solid biomass or black liquor from a chemical pulp mill, and produce many different products. Some examples of products that can be produced are electricity and heat or synthesis gas that can be upgraded to fuels (and chemicals) like methanol, ethanol, methane, FT diesel, DME and hydrogen.

The separation and refining category includes a wide range of technologies that can be used to separate basic components of biomass, i.e. cellulose, hemicelluloses, lignin and extractives. Some examples of the final products that could be produced are ethanol from acid or enzymatic hydrolysis of cellulose followed by fermentation. Ethanol can also be produced by refining of hemicelluloses from black liquor or solid biomass. Separation of lignin could be used for production of fuel, phenols, plastic materials, carbon fibres, dispersants and binders.

# 3 Theoretical framework

This section presents a theoretical framework for analyses of resource mobilisation to support the complex and time-consuming process of development and, particularly, diffusion of technology. The process of technology diffusion can be described in terms of an initial development phase followed by take-off, a growth phase and a saturation phase. The technologies that this thesis focuses on, offshore wind power and biorefinery technologies, respectively, are in a development phase. However, looking at the expected development of offshore wind power it seems that a take-off and growth phase could be near, as the estimated annual installations in the coming two decades imply a rapidly increasing rate of installations (Figure 2). The development of biorefinery technologies is in a development state (see e.g. Hellsmark (2010) for the development of gasification technology).

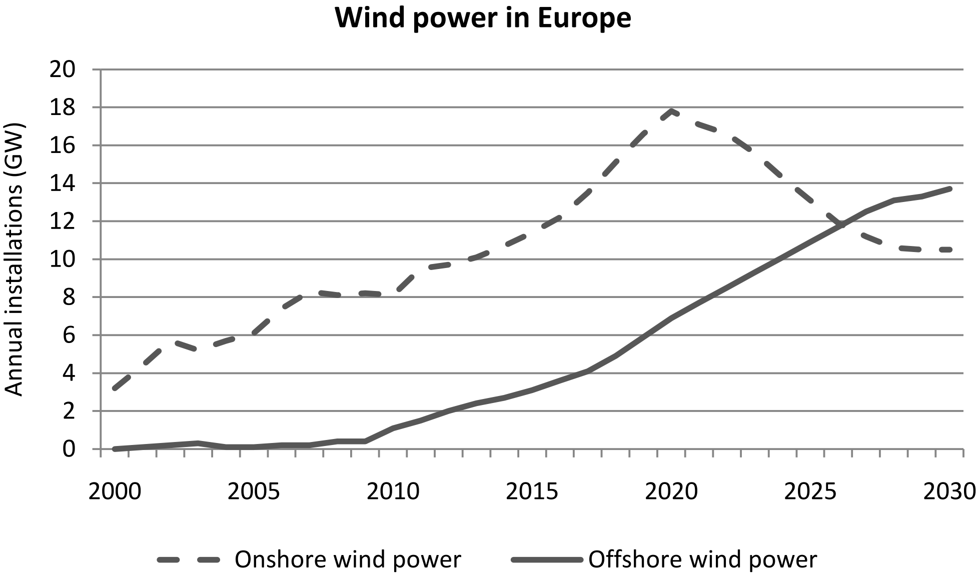

**Figure 2** The annual installations of offshore wind power have been modest so far, but a scenario by EWEA (2009b) estimates that the installations will increase rapidly in the coming years to reach a more saturated level by 2030. According to the estimate, today we are just before a take-off.

For take-off and entering into a growth phase, resource mobilisation is a critical challenge. The processes behind resource mobilisation are partially social. To gain an understanding of resource mobilisation for technology diffusion will therefore entail studies of social and technical aspects and their interplay. Hence we need to study the socio-technical system in which the technology is embedded.

## *3.1 Socio-technical systems*

A system consists of components and relations between these components; the components together form an entirety (Ingelstam 2002). The components are inside the system boundaries, surrounded by the system environment. Socio-technical systems centre on a technical system, e.g. the energy system, but in order to study this technical system it cannot be separated from the societal system in which it exists and vice versa (Ingelstam 2002). There are several socio-technical system models that could be used to describe the systems studied in this thesis, e.g. large technical systems (Hughes 1987) and different models of innovation systems. The first model was developed to analyze how large technical systems evolve and persist, while the second focuses on innovation activities for development, diffusion and use of new technology. These system models have emerged from evolutionary economics, which regards an economy as a complex and varied system that evolves over time as new options evolve and disappear in a process of creative destruction (Schumpeter 1942; Rosenberg 1994). There are several innovation system models that differ in terms of system boundaries; e.g. innovation systems are analyzed with national, regional, sectoral or technological system boundaries.

A technological innovation system framework would be suitable for the analysis of the offshore wind power sector in Paper I (see for example the analysis of resource mobilisation for rapid and sustained diffusion of novel technology in Jacobsson and Bergek (2004)). In Paper II another framework is used for the analysis: the multi-level perspective (MLP) for analysis of technological transitions (Rip and Kemp 1998; Geels 2002; Geels and Schot 2007). The framework developed in this thesis uses central concepts from both innovation systems literature and MLP to define a socio-technical system with different system levels. A similar model that integrates technological innovation systems and the multi-level framework has been suggested by Markard and Truffer (2008b).

## *3.2 Several levels of a socio-technical system*

The multi-level perspective differentiates between of three analytical levels: niches, regimes and landscape. Several analytical levels are also acknowledged within the literature of innovation systems (see e.g. Ehrnberg and Jacobsson 1997). Initially, development of a technology can be supported by strategic management of *niches* in which the technology is applied (Kemp et al. 1998). The niche can function as an incubator room where an innovation is protected from mainstream market selection, since the selection criteria differ between the niche and its environment. Additionally, within the niche it is possible to find locations for learning processes and building of social networks that support innovations. The niche concept is similar to the socio-technical system outlined in a technological innovation system. For a more large-scale diffusion of the technology, also *socio-technical regimes* will be affected; or rather, for a technology to diffuse on a large scale, changes in regimes are needed. Both niches and regimes are embedded in the *socio-technical landscape* that forms the external macro-level. The landscape consists of factors that influence the development and diffusion of the technology, but without being influenced by the outcome of this process (Markard and Truffer 2008b).

There is no unambiguous regime definition. The concept is developed from Nelson and Winter's (1977) technological regime, which relates to technicians' beliefs about what is feasible and desirable.[14] Rip and Kemp (1998, p. 338) use a broader perspective and define the technological regime as *the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, ways of defining problems — all of them embedded in institutions and infrastructures.* Geels (2002, p 1260) broadens the concept even more by including all types of rules, and describes a socio-technical regime as *a semi-coherent set of rules carried by different social groups.* These rules guide innovation activities towards incremental improvements of established socio-technical systems and create stability (Geels and Schot 2007). In this thesis a definition is applied which was inspired by Holtz et al. (2008) and which, in addition, includes other elements such as actors and artefacts.[15] This definition of a regime is similar to that of a sector, and a framework of a sectoral innovation system could also be used for the analysis conducted in Paper II.

Defining the niche as a technological innovation system and expanding the regime concept to include not only institutions (but also actors and artefacts), makes niches and regimes similar in terms of structural components. The analysis in Paper I is conducted at the niche level, while the analysis in Paper II is conducted at regime level. For these analyses the defined socio-technical system includes the same structural components. The following components are included: technology, actors, institutions and networks (Bergek et al. 2008b). Technology can be defined as artefacts or hardware, but also includes the industrial arrangement required for design and manufacturing of these artefacts, related systems (e.g. power grids for the installation of wind power offshore), and the knowledge base needed for production and use of the technology (Grübler 1996). Actors are firms, organizations or individuals that are involved in the development and diffusion of the technology, such as firms along the supply chain, universities, industry associations, interest organizations and government bodies (Bergek et al. 2008b). Institutions are culture, norms, laws, regulations and routines. Networks can be formed between actors, for example in the form of supply chains (Bergek et al. 2008a).

## *3.3 Mobilisation of resources*

Mobilisation of resources is identified as one of several important functions for the development and diffusion of technology in the literature of technological innovation systems (Jacobsson and Bergek 2004; Bergek et al. 2008a). The different functions are not interdependent of one another and changes in the resource mobilisation might affect other functions and vice versa. Resources that need to be mobilised to support diffusion of

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[14] The conception can be associated with Dosi's (1982, p. 148) technological paradigm, which is an "outlook", a set of procedures, a definition of the "relevant" problems and of the specific knowledge related to the solution. A technological paradigm guides the direction of progress in a technological trajectory (Dosi 1982).

[15] Holtz et al. (2008, p. 629) identify five characteristics of a regime, and include actors when they summarize these characteristics in the following definition: *A regime comprises a coherent configuration of technological, institutional, economic, social, cognitive and physical elements and actors with individual goals, values and beliefs. A regime relates to one or several particular societal functions bearing on basic human needs.*

technology are e.g. human capital, financial capital and other assets such as infrastructure, services and raw material (Bergek et al. 2008a). These resources are controlled by different actors; e.g. incumbent firms are often in control of manufacturing infrastructure, raw material and human capital, while universities affect the formation of new human capital.

For the analysis of resource mobilisation in this thesis, a methodological approach for estimating the need for competences both qualitatively and quantitatively is developed in Paper I (see section 2 in Paper I). For the analysis in Paper II, a theoretical framework that combines literature on strategic management and transition management is developed. This framework is summarized in the following section.

## *3.4 Firms and systems*

Changes at landscape level may create a pressure on the regime, which could lead to a weakening in this level and create a window of opportunity for diffusion of technology (Geels 2002).[16] To understand a regime change it is important to acknowledge the diversity among incumbent firms. Therefore, an attempt is made to develop a more fine-grained description of regime changes by applying some fundamental ideas from the strategic management literature. This is recognized also by Geels (2010) who argue that findings from the strategic management literature could enrich the MLP framework.

The strategic management literature explicitly acknowledges firm diversity. Porter (1985) analyses a firm’s competitive strategy with an analytical framework based on the attractiveness of the industry and on the position taken by the firm within this industry. The industry’s attractiveness is affected by five competitive forces: bargaining power of buyers, bargaining power of suppliers, threat of new entrants, threat of substitutes, and rivalry among existing firms (Porter 1985). In Paper II, the five-force model is used to translate broad trends, or landscape changes, into forces that put pressure on incumbent firms in the industry. The five-force model can then be used to analyse changes within the industry. Depending on how firms are positioned, they will be more or less exposed to different pressures and also react differently.

A complementary perspective is offered by the resource-based view. Grant (1991) claims that a firm’s competitive position is best explained by its resources and capabilities. Therefore, a firm should identify its internal resources and skills and match these against the opportunities and risks created by its external environment. Hence, one would expect that firms with different resources (e.g. competences) would search for new opportunities in different directions.

Additionally, few strategic management theories assume that firms are acting in accordance with some universal rationality. Instead, managers, like all humans, are guided by mental

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[16] The linkages between micro and meso levels in an innovation system are analysed by e.g. Markard and Truffer (2008a).

models, which are used as filters to simplify reality and enable decision-making (Foster and Kaplan 2001). These models are based on successes and failures of previous actions, but are seldom explicit. Hence, it can be assumed that the response of different firms to external pressures would depend not only on their resources and strategic positioning, but also on less tangible traits like company culture.

This basic strategic management literature can give a more nuanced view of the actions of incumbent firms and thereby contribute to a deeper understanding of regime changes.

# 4 Resource mobilisation for energy system transformation

This section analyses two perspectives of resource mobilisation for development and diffusion of technology. First, the mobilisation of human capital or competences is analysed. In this analysis, there is a particular focus on the need for engineering competences in the emerging offshore wind energy sector (Paper I). Second, an analysis is made of an incumbent industry in control of raw material, competences and technical systems and which, therefore, can hinder or drive the development of technology. This is illustrated with the transformation process of the Swedish pulp and paper industry, in particular the adoption of biorefinery options (Paper II).

## *4.1 Mobilisation of competences for offshore wind power*

The industry emerging around offshore wind power faces many challenges that must be overcome to expand this industry. One cause of these challenges is lack of infrastructural investments for development of offshore wind power. This includes limited transmission capacity to offshore sites as well as an associated lack of integration of offshore wind capacity into the European grid system. Other infrastructural bottlenecks are lack of specially built vessels for transporting and installing offshore turbines, the supply of substructures, and shortages in adapted ports for supplying the offshore market (EWEA 2009a; Giese 2010). Furthermore, institutions are not aligned to offshore wind power. This refers to, for example, uncertainties in funding of grid connections, national differences in market mechanisms, which hamper efficient trade, and lack of integrated maritime planning (EWEA 2009a). These challenges generate uncertainties for investors and may make it harder to finance the expensive offshore wind power projects.

In addition to the challenges outlined above, there are many technical challenges for the design of offshore wind turbines. These challenges can be summarized as follows. Turbines must be adjusted to the offshore environment, including exposure to water, sun, salt and wind. The electrical components (e.g. generators), control system and structural components such as rotors must be developed for the up-scaled offshore turbines (5-6 MW instead of 2-3 MW onshore turbines). Additionally, the components must interact in a manner that ensures dynamic stability. Furthermore, offshore wind turbines require support structure and sufficient grid integration to function. There is also a lack of metrological knowledge for operations offshore, which hinders the development of offshore wind power. To meet these challenges, there is a demand for engineering competences.

### 4.1.1 Engineering competences needed for offshore wind power

The engineering competences needed to realize the potential of offshore wind power are analysed in terms of types and numbers. The types of engineering competences are derived largely from an analysis of the technical challenges, described briefly above (and in more detail in Paper I). The needed types of engineering competences include deep competences within a knowledge field, not only electrical and mechanical engineering, but also other fields such as civil engineering and engineering physics. Integrated competences are also needed, both within engineering fields and with other fields, such as meteorology and management. A summary of these competences is presented in Table 2.

**Table 2** Engineering competences needed for the realization of the potential of offshore wind energy in the North Sea.

| Deep competences | Integrated competences |
|---|---|
| Specialized mechanical engineering | Integrated mechanical and electrical engineering |
| Specialized electrical engineering | Health, environment and safety (HES), and operation and maintenance (O&M) respectively integrated into other competences |
| Software engineering | Integrated mechanical engineering |
| Engineering physics | Integrated engineering competences and meteorology |
| Civil engineering | Engineering competences integrated with project management |

For estimation of the order of magnitude of engineers needed to realise this potential, the fact that onshore wind is still expanding has to be kept in mind. Calculations of the number of additional engineers needed until 2020 are made for two categories, wind turbine manufacturers and utilities. As the value chain is much larger, these estimates are cautious. For wind turbine manufacturers, data from the interviews are used to calculate a ratio of annual production per engineer. For utilities, a ratio of expected total installed capacity per engineer, from 2009 to 2020, is calculated. The EWEA (2009b) scenario (Figure 2) is used to calculate the total number of engineers needed at the industry scale. For wind turbine manufacturers, the annual ratio is 2.3 MW per engineer, for both onshore and offshore wind. This is applied to the estimated increase in annual production of 16.2 GW. For utilities the ratio for only offshore wind is 14.3 MW per engineer. This is applied to the total installations needed during 2009 – 2020 of 38.1 GW. The ratio of output per engineer is assumed to be constant until 2020 due to the challenges (of technical, infrastructural and institutional character) that face wind power.

The calculations show that until 2020, there is a need for an additional 7 000 engineers at the wind turbine manufacturers for production of both onshore and offshore turbines. The calculation for utilities shows that an additional 2 000 engineers for offshore alone, are needed until 2020. The real number is, however, probably considerably larger since the ratio used in this calculation only takes into account in-house engineers at the utilities. Consultancy firms assist utilities and other firms along the value chain with a wide range of activities. Moreover, component suppliers are not included in the calculations and still more engineers are required for the design and manufacturing of installation vessels, foundations and cranes, and for enlarging the electrical grid (Ström Madsen 2010). Hence, whereas the number of engineers that will be required by turbine manufacturers and utilities is estimated to be around 9 000, it is likely that the number of engineers needed in the whole value chain may easily go beyond 10 000.

### 4.1.2 Implications for universities

Industry, of course, recruits staff from a range of related industries. Yet, as industry expands in line with the scenario in Figure 2, the particular needs of the wind energy industry should arguably be reflected in the programmes and curricula at the universities. A central task for universities is, therefore, to ensure that competences are built in appropriate variety and volume, and in a timely fashion. Many of the competences required are of general nature, and engineers can be recruited from a range of related industries. There is a handful of dedicated wind energy MSc programmes in the countries around the North Sea and new programmes are in the pipeline at several universities. Still, there is a need for more programmes to develop both deep competences and integrative competences, including a number of different possible combinations. The main bottleneck in terms of deep competence is a shortage of electrical engineers (e.g. Arndt 2010; Normark 2009; Bak-Jensen, 2010; Hohmeyer 2010), but other competences are needed such as mechanical engineering, physics, meteorology, civil and software engineering.

Also integrative competences need to be developed to a greater extent. Perhaps the most challenging integrative competence is that which combines electrical and mechanical engineering (Nörker Sörensen 2010). Integrating these fields in the same educational programme will require students who are excellent in e.g. mathematics and programming, and that a resistance to cross-disciplinary work is overcome (Hauge Madsen and Larsen 2010; Nörker Sörensen 2010). Additionally, a dedicated MSc programme in offshore project management is required, as it is a vital competence among both turbine manufactures and utilities (Möller 2010). Such a programme should provide an understanding of the various technical components, but also of logistics, meteorology, maintenance (Giese 2010), risk management (Möller 2010) and communication (Cooke et al., 2010).

Expanding the number and types of programmes requires that the teaching staffs are enlarged. It may also require that a European portfolio of specialized courses is organizationally integrated and made easily available to students from universities taking part in the program.

## *4.2 Mobilisation of resources controlled by an incumbent industry*

The Swedish pulp and paper industry is in control of biomass raw material, competence and technical systems that are needed for large scale diffusion of biorefinery options. A biorefinery can be described as a mill that converts biomass not only to conventional fibres for paper products, but also to other materials, chemicals and energy carriers. Many of these technologies have been developed by niche actors during several decades, supported mainly by public funding (Sandén and Jonasson 2005; Hellsmark 2010). The Swedish pulp and paper industry has demonstrated little interest in this development, but the industry has changed its attitude about how to use biomass resources since it has been under pressure from several changes at landscape level (Ottosson 2011). None of these changes have had only negative effects on the industry, but they have all urged the industry to react in some way.

### 4.2.1 Landscape changes affecting an incumbent industry

There are mainly three changes at landscape level that have affected the industry: increased attention to energy and environmental issues, the rise of ICT and economic growth in South America and Asia. The increased concern about climate change and security of energy of supply have resulted in several policy measures that in turn are affecting energy and feedstock prices, including biomass feedstock. The deregulation of the electricity market has caused increased electricity prices. On the other hand, the Swedish green certificates have opened up an opportunity for a new revenue stream for pulp plants that can generate electricity. Moreover, the debate on environmental issues has contributed to increased demand for biomass-based personal care and packaging products (Jääskeläinen 2009).

While the debate on environmental issues might have increased demand for some products, it is believed that competition from electronic media has led to decreased demand for newsprint on the European, North American and Japanese markets (Jääskeläinen 2009; Andersson 2010). However, the statistical evidence of a downturn in demand for newsprint is not compelling. The demand for newsprint in Europe remained stable at 11-12 per cent of total paper demand between 2005 and 2009 (Swedish Forest Industries 2010b).

The rapid economic growth in other parts of the world has opened potential new markets. This implies a geographical shift of potential future markets, from Europe and North America to Asia and Latin America (Axegård 2009; Wikström 2009). However, increased production capacity in South America and Asia reduces the possibility for European companies to take advantage of these emerging markets. Instead, the pulp and paper industry in Europe now meets increased competition from firms in countries outside Europe with lower production and feedstock costs. Despite this, the European firms seem to remain in a strong position on the European market. For example in 2009 Asia, Africa and South America collectively delivered only around one per cent of the paper consumed in Europe (Swedish Forest Industries 2010a).

The combined effect of these changes is seen in the profitability of the industry, which is dwindling. Since 2000, the surplus has almost vanished due to limited growth in output and continuously growing costs for input goods (Statistics Sweden 2011). As a result of this increased pressure, firms within the industry seems more interested in searching for new options than they have been before (Berntsson 2010).

### 4.2.2 Industry responses

Industry responses, such as efficiency improvement of current processes, take place in the whole industry. Other responses, such as vertical integration to reduce cost and reach new markets, are only pursued by some. A more radical response would be to enter new value chains by developing new products and new technologies. This can be done by developing biorefinery concepts that offer new business opportunities for firms in the industry, but they also represent a challenge. They entail large investment in new process technology and in knowledge and networks required to enter new markets. Furthermore, some biorefinery configurations challenge current business models (Chambost and Stuart 2007). Few companies have gone so far that they have actually started to implement radically new technologies, but many are engaged in research and demonstration projects to investigate options that can convert their mills into biorefineries. Development of these technological options can be identified along two technological trajectories.

The first trajectory is centred on gasification technologies. Companies that are interested in gasification tend to focus on production of biofuels rather than chemicals and bioplastics, which equally well could be produced. In most cases, the companies are interested in gasifying low-grade biomass in parallel with continued production of pulp or paper. Integration of this technology implies major investments in new technology, but the change in business model is minor.

The processes employed in the second trajectory are typically enzymatic processes, hydrolysis and fermentation. Compared to gasification technology, the choice of process is linked more directly to a specific product. Companies on this trajectory have a broader perspective on the kind of products they may produce in the future – chemicals, materials and possibly fuels. The business model linked to production of chemicals and materials focuses on the possibility to sell small quantities of these products at a high price.

### 4.2.3 Explaining industry response with strategic management

To understand the response from this incumbent industry, it is important to observe the initial heterogeneity among the firms. First, the technical system matters. The type of mill is important for the attractiveness of biorefinery options. There are mechanical mills and chemical mills; some produce only pulp and some integrate pulp and paper production. The incentives and technical possibilities to implement biorefinery options are largest in non-integrated chemical pulp mills, due to their positive energy balance and availability of large amounts of by-products (Berntsson 2010). Thus, most mills involved in development of biorefinery options are chemical pulp mills. Also the type of biomass feedstock that is available to different mills sets limits to what can be produced and which processes can be used (Smook 2002).

Second, competence and knowledge base influence the response. The industry has traditionally done a lot of research on cellulose fibre. Thus, for development of the second trajectory, knowledge about cellulose fibres for production of materials and chemicals can relate to one of the industry’s core competences.

Third, firms have different positions within the industry and are therefore exposed differently to the pressures. This could concern extent of vertical integration, size and kind of mills and products. For example, large companies, such as Stora Enso, can expand internationally and establish mills in Asia and South America in order to access the growing markets and low-cost feedstock in these countries.

Fourth, mental models, based on successes and failures of previous actions, are used as a filter to simplify reality and enable decision-making (Foster and Kaplan 2001). An example of this is the creation of Domsjö Fabriker, which was bought from the corporation MoDo by a small group of people who have long been active in the industry. In contrast to the former owner, who was planning to shut down the mill, the new owner group had an alternative mental model and was convinced that the unprofitable pulp mill could be transformed into a modern biorefinery (Norlin 2010). To summarize, the firms have different prerequisites, regarding resources and capabilities, position within the industry and previous experiences, for responding to these changes (Figure 3).

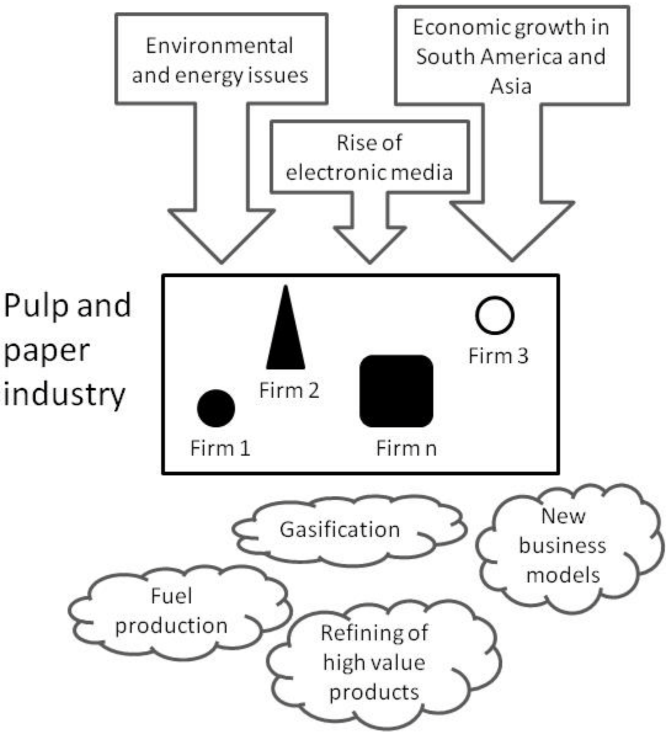

**Figure 3** The Swedish pulp and paper industry is affected by pressure from landscape changes, including environmental and energy issues, rise of ICT and economic growth in South America and Asia. Furthermore, within the industry the firms have different prerequisites, regarding resources and capabilities, position within the industry and previous experiences, for their reactions. There is also a range of different opportunities in terms of technological options and products, as well as in development of new business models.

To summarize, exogenous trends, or landscape changes, can be translated into forces that directly affect the overall profitability in the industry. Four out of five forces in Porter's model are developing in a direction that should drive down profits. The bargaining power of suppliers is increasing, resulting in higher prices for input goods such as energy and biomass feedstock. The threat of substitutes (such as electronic media) is increasing for some products, which reduces the possibility to raise prices to increase revenues. The development in South America and Asia increases rivalry among existing firms in Europe/Sweden and creates a threat of new entrants on the European market. These changes create a pressure on the incumbent industry which has increased the motivation to get involved in development of biorefinery options. To understand this response, it is essential to observe the heterogeneity of the firms within the industry, regarding resources, skills, position and experience from previous actions. The responses of the firms in the industry that can be identified today can be seen as an initial phase of a regime fragmentation, i.e. firms within the industry are developing in different directions and the structure of the regime is beginning to weaken. This could constitute a starting point for a transition.

#### 4.2.4 Blurring industry boundaries

In common for the development of biorefineries and offshore wind is that it links actors from different industries to each other via physical resources (e.g. raw material such as biomass) and/or knowledge. In the case of biorefineries, various energy companies that previously have converted biomass to heat and electricity are now planning large demonstration plants for production of biofuel. The development of different types of biorefinery concepts for production of chemicals and fuels also attracts the chemical industry, the oil and gas industry and the car industry. The same seems to apply to the development of offshore wind energy that, for example, also attracts the oil and gas industry which has competence in offshore engineering and knows how to operate units at sea. Industry boundaries will be blurred and the development and diffusion of both biorefineries and offshore wind turbines will involve actors from several industries.

# 5 Conclusions

A transition to a sustainable path of development will require that fossil fuels are replaced with renewable energy sources and involve a large scale transformation of the energy system. In the EU, offshore wind power and biorefineries have the potential to play an important role in this transformation, but to achieve a large-scale expansion of these technologies there is a need for resource mobilisation. This thesis scrutinizes two perspectives of resource mobilisation for development and diffusion of new technologies: the mobilisation of human capital or competences and the behaviour of an incumbent industry in control of raw material, competence and technical systems which is needed for development of technology.

The analysis of human capital or competence needed to realize an expansion of offshore wind energy, shows that there is a need for both deep and integrated competences. The challenge is, however, not only to generate a rich variety of competences but also to make sure that a large number of engineers are available to the industry. It is likely that the number of additional engineers needed in the value chain may easily go beyond 10 000. This formation of required competences has implications for the universities, which can facilitate an industrial transformation by an expansion in the number and types of educational programmes in accordance with expected demand.

The analysis of the pulp and paper industry shows how the industry has started to change its attitude towards development of biorefinery technologies. This change has started since the industry has been put under pressure from several changes at a societal level. This far, the industry’s reaction to these changes has been modest and is characterized by incremental change. However, development along two new technological trajectories can also be identified. The first concerns gasification of large volumes of biomass or black liquor for fuel production with a business model similar to the current one. The second, separation and refining for production of high-value products, requires a modified business model. The firms’ different reactions to pressure can be explained by their different prerequisites regarding resources, skills, position and experience. These reactions can be seen as an initial phase of a regime fragmentation, i.e. firms within the industry are developing in different directions and the regime is beginning to weaken. This could constitute a starting point for a transition.

The theoretical framework presented in this thesis combines literature on transition management, innovations systems and strategic management. It can be concluded that this combination contributes to a deeper understanding of the interactions between the different system levels, e.g. firm, technology, niche, regime/sector and landscape. Additionally, the need for mobilisation of human capital for a transformation (of the offshore wind power sector) is emphasised in this thesis. A methodological model of the demand for competence (type and number) is developed for the analysis in Paper I.

Finally, two implications for policy makers can be drawn from the conclusions above. First, expanding the type and number of university programmes will require that the associated teaching staffs are enlarged. This might, in turn, require an expansion of funding for research if teaching is to be linked to research. Additionally, this expansion may require support for a European portfolio of specialized courses that are organizationally integrated and made easily available to students from different universities.

The second implication concerns the ambitions to utilise biomass resource in other applications than pulp and paper. The pressure from policy alone has not been enough to stimulate the pulp and paper industry to take action. However, the combined pressure from several changes at the landscape level has created a tension in the industry that has urged firms to react in the form of uncoordinated experimentation in many directions. Hence, policy-makers who aim at stimulating a transition need to consider that firms are diverse and that there exist multiple pressures as well as multiple new opportunities. This will cause firms to react very differently to any policy that is implemented. Given the great uncertainty, this diverse experimentation may be desirable.

# 6 Further research

From the results and conclusions of this thesis, four themes that could form further research are identified. The importance of competences and the role of the universities for a large-scale diffusion of offshore wind power have been underlined in Paper I. To support a transformation of the energy sector, where fossil fuel is replaced by renewable sources, it would be valuable to extend the analysis of demand for competences to include other energy technologies or the whole energy system. A next step in this particular research project could be to apply the methodology developed in Paper I to the empirical field of Paper II, thus analysing the demand for competences (including type and number) for the realization of biorefinery technologies.

The theoretical framework presented in this thesis could be further developed, by describing the linkages between different levels (e.g. firm, technology, niche, regime/sector and landscape) in more detail. This could be done by a more thorough incorporation of literature from strategic management to transition management or innovation systems literature. To change the empirical view from Paper II, the empirical field of Paper I could be used in a future study that scrutinizes strategies of one (or a few) companies in the wind power industry. For examples, the role of utilities and why some turbine manufactures are interested in develop of offshore turbines, while others are not.

In addition, the studies included in this thesis demonstrate how actors from different industries, which until now have operated in separate sectors, become linked via development of technology. The expansion of these technologies is motivated by environmental concerns, although the involvements of different industries are most likely due to different reasons. Possibly environmental concerns are one of them, but not necessarily the only one. This thesis has focused on development of technology from the perspective of *one* industry at the time. A possible next step could be a study of the motivation of firms in the various industries that are involved (or could be involved) in the development of an energy technology.

Another theoretical reflection for further research is the consideration of the ecological system in a sustainable transition. There are many linkages between the studied socio-technical systems and the socio-ecological systems that they form. However, even though the diffusion of the technologies studied in this thesis could contribute to what is defined as a sustainable transition, the theoretical framework does not include the ecological system. Impacts from a socio-technical system on a socio-ecological system will most likely increase as the socio-technical system expands. Therefore this aspect is of great concern for a research project with focus on large-scale technology diffusion.

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A transformation of the energy system to a sustainable path of development is urgently needed. This will require a shift from fossil fuels to renewable energy sources. In EU, offshore wind power and biorefineries have the potential to play an important role in this shift.

This thesis analyse mobilisation of resources needed to achieve a large-scale installation of these technologies. First, the need for competences in the offshore wind sector is analysed. Second, the actions of the pulp and paper industry that is in control of biomass resources and which, therefore, can hinder or drive the development of biorefinery technology is analysed. To conduct this analysis an analytical framework based on several literature strands is used.