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Biomass Gasification
The characteristics of technology development and the rate of learning

Master's Thesis

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EXECUTIVE SUMMARY

Gasification is considered one of the most promising technologies in biomass applications. The higher efficiency compared to boiler power systems, the perspectives in fuel synthesis and its environmental friendly features are some examples of its potential. Biomass gasification has evolved since its first applications, but it has not been possible to reach a solid commercial stage, except during periods of crises and only for some specific applications. Meanwhile, other gasification technologies, fed by fossil fuels, are currently widely used on industrial scales.

This thesis aims to analyze the knowledge development and diffusion patterns of the biomass gasification technology since 1970's in Austria, Finland, Germany and Sweden. Additionally, it seeks to identify the factors that strengthen and weaken the learning process. Finally, the concept of learning curve will be used to numerically assess the rate of learning in small scale biomass gasification for electricity generation. The feasibility of various future scenarios will be evaluated in order to know what is the likelihood for the technology to become competitive in the short term.

To do so, the historical evolution of biomass gasification in Austria, Finland, Germany and Sweden has been analyzed. These countries have been selected due to the increasing number of ongoing projects and initiatives since 1970. Subsequently, the development of this technology has been encouraged by two historical facts. Initially, the price of fossil fuels grew in 1973 and 1979 enhancing the interest for biomass gasification as a future alternative. Afterwards, the willigness, shown by the mentioned countries, to reduce greenhouse gases emissions following the Kyoto protocol has revived the interest in biomass gasification. However, none of these two events has driven this technology sufficiently to achieve a sustainable commercial status. In addition, small and large scale projects have followed different development processes. In the case of large scale, interest has shifted from electricity generation to biofuel production, primarily due to the failed demonstration projects of the technology coupled with combined cycle for electricity generation. On the other hand, in small scale projects, cogeneration applications have gained interest over heat production. However, there are fewer actors involved in small scale experimentation than in large scale.

Once the specific situation of each country has been analyzed, and the main characteristics of the development process have been identified, one of the causes which have hindered the technology to reach the expected commercial stage has been the lack of resources to demonstrate its competitiveness. So far, a significant number of experimentation activities, based on demonstration projects and pilot plants, have proved the future potential of the technology. Nonetheless, the uncertainty, shown by the great majority of actors, about integrating the biomass gasification in their industrial process has hindered the demonstration of its operational feasibility. Following this, further efforts should focus on the creation of incentives for the construction of new plants which integrate this technology in an

industrial process already consolidated in the market. An approximation of the number of new plants needed, could be a good indicator of the economical resources required in order to acquire enough experience to make biomass gasification a competitive technology in the short-term.

After simulating various future evolutions for small scale cogeneration applications, the learning rate obtained through the *learning curves* model predict that, building roughly forty plants in six years, the technology can be consolidated firmly in the market. Considering the decrease in the number of new plants built since 2002, the expectancies are not really optimistic. Nevertheless, it is not an unachievable objective if incentives are created by all administrative levels.

RESUMEN EJECUTIVO

La gasificación de la biomasa es una tecnología que ha demostrado tener mucho potencial de futuro pero que nunca se ha llegado a comercializar de forma satisfactoria. El objetivo del presente proyecto consiste en analizar cómo se ha desarrollado la base de conocimiento de esta tecnología, su difusión, así como el tipo de actividades de investigación que se han llevado a cabo y las empresas que han intervenido. De esta forma, se ha intentado dar una explicación a la falta de competitividad de esta tecnología en comparación con otras, también basadas en el uso de la biomasa.

Para ello se ha analizado la evolución histórica de la gasificación de la biomasa en Austria, Finlandia, Alemania y Suecia. Se han elegido estos cuatro países debido al creciente número de proyectos e iniciativas surgidas desde 1970. De esta forma, se ha observado como la tecnología se ha visto impulsada fundamentalmente por dos causas históricas. Inicialmente, los aumentos de precio de los combustibles fósiles en los años 1973 y 1979 incrementaron el interés por la gasificación de la biomasa como posible alternativa de futuro. Posteriormente, el compromiso de estos países con las directivas europeas respecto a la emisión de contaminantes, realzaron el interés por la misma. Sin embargo, ninguno de estos dos sucesos ha impulsado suficientemente esta tecnología para alcanzar un estado comercial sostenible. Además, ha existido un proceso de desarrollo diferente para proyectos de pequeña y gran escala. En el caso de los proyectos a gran escala, el interés ha cambiado de la generación de electricidad a la producción de biocombustibles debido, en gran parte, a la multitud de proyectos fallidos destinados a la demostración de la tecnología acoplada a ciclos combinados para la generación de electricidad. Por otro lado, en las instalaciones de pequeña escala, las aplicaciones de cogeneración han ganado interés por encima de aquellas destinadas a la producción de calor. Sin embargo, el número de actores que han intervenido en su desarrollo ha sido muy inferior en comparación con los de gran escala.

Después de analizar más específicamente la situación en cada uno de los países y poner en común sus principales rasgos de desarrollo, una de las causas que ha hecho que la tecnología no haya alcanzado el éxito comercial esperado es la falta de recursos para demostrar su competitividad. Hasta el momento,

un importante número de actividades de investigación basadas en proyectos de demostración y plantas piloto han reafirmado el potencial de futuro de la tecnología. Sin embargo, la incertidumbre mostrada por la mayoría de actores para integrar la gasificación de la biomasa en su proceso industrial, ha impedido demostrar la viabilidad operativa de la misma. De esta forma, los esfuerzos deben ir dirigidos hacia la creación de incentivos para la construcción de nuevas plantas que integren esta tecnología en un proceso industrial ya consolidado. Una aproximación del número de plantas a construir en un futuro podría ser un buen indicador de los recursos económicos necesarios para adquirir suficiente experiencia y poder hacer de la gasificación una tecnología competitiva a corto plazo.

Una vez simuladas diferentes evoluciones futuras para aplicaciones de cogeneración a pequeña escala, las tasas de desarrollo obtenidas a partir del modelo de "*learning curves*" predicen que construyendo alrededor de cuarenta plantas en seis años, esta tecnología podría consolidarse firmemente en el mercado. Considerando la disminución del número de plantas construidas en los últimos diez años, las perspectivas no son muy optimistas. Sin embargo, no se trata de un objetivo inalcanzable si se incentiva correctamente desde todos los niveles políticos e institucionales.

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ACRONYMS

BFB	Bubbling Fluidized Bed
BIGCC	Biomass Integrated Gasification Combined Cycle
BMG	Biomass gasification
BLG	Black Liquor Gasification
CFB	Circulating Fluidized Bed
CHP	Combined Heat and Power
DD	Downdraft
DME	Di Methyl Ether
EC	European Commission
EF	Entrained Flow
F-T	Fischer Tropsch
HHV	High Heating Value
LR	Learning Rate
MSW	Municipal Solid Waste
RDF	Refuse Derived Fuel
STEM	Swedish National Agency Administration
UD	Updraft

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1 INTRODUCTION

1.1 Background

Gasification is considered one of the most promising technologies in biomass applications. The higher efficiency compared to boiler power systems, the perspectives in fuel synthesis and its environmental friendly features are some examples of its potential. Biomass gasification has evolved since it first applications, but it has not been possible to reach a solid commercial stage, except during periods of crises. While other gasification technologies, fed by fossil fuels, are currently widely used on industrial scales. Since the 1950's, the technology has evolved trying to find a niche market that allows it to go from demonstration concepts to commercial applications. However, there have been several failed projects and consequently its legitimacy has weakened drastically. It is clear that something is failing in the system, hindering a commercial success. In this thesis, we set out to analyse the technology development and rate of learning of biomass gasification since the 1970's. The objective is to give some suggestions on what is hindering a commercial breakthrough with respect to the current rate of knowledge development and entrepreneurial experimentations.

As BMG is still considered an emerging technology, its development is strongly dependent on further progress in various areas. A powerful tool that can be used to analyze it, is the *Technology Innovations Systems (TIS) approach.*. This approach simplifies the analysis, dividing it in seven parts based on seven functions. Each function deals with different aspects of the system performance. This thesis aims to study only two of these functions, giving the chance to use its conclusions in a complete system analysis. In order to analyze both of them, some indicators will be presented and commented. The two chosen functions are *Knowledge development and diffusion*, and *Entrepreneurial experimentation*. While the first one "captures the breadth and depth of the knowledge base and how well that knowledge is diffused and combined", the second, describes how entrepreneurs are "probing into new technologies and applications" (Bergek 2008). Thus, by analysing both of them, the learning process can be entirely described and assessed.

To study these two functions, we have selected four countries that have demonstrated to play an important role in research and development activities related with the technology. These are Austria, Finland, Germany and Sweden. Trends in technology development present different characteristics in each country, concerning applications, research direction and networking among actors. However, in all of them, there have been important successful projects that have helped furthering the technology development. Consequently, understanding what factors are strengthening or weakening the learning process in each country would contribute to obtain some interesting conclusions on how to improve the competitiveness of the technology.

The starting point of this thesis has been established in 1970, during the first oil crises, until present day 2008. In the history of BMG, oil crises have played a major role in the interest for the technology, creating new expectancies about its future role. Moreover, since 1970, the amount of available data about undertaken projects has increased thanks to the formation of knowledge networks, concerned about the know-how and experience sharing.

1.2 Purpose

Many economical and technical studies of biomass gasification have been carried out ((Bolhàr 2004), (Knoef 2005) or (Kwant 2004)). However, the features of the knowledge development, rate of learning and entrepreneurial experiments in these studies have not been connected in order to analyse the individual factors that hinders the commercialisation of the technology.

Hence, our objective is to give some suggestions on what is hindering a commercial breakthrough with respect to the current rate of knowledge development and entrepreneurial experimentations. In order to fulfil the objective, we set out to,

a) *Analyze the knowledge development and diffusion patterns of the biomass gasification technology since 1970's in Austria, Finland, Germany and Sweden.*
b) *Identify the factors that strengthen and weaken the function of knowledge development and diffusion and the function of entrepreneurial experimentation.*
c) Finally, the concept of learning curve will be used to *numerically assess the rate of learning in small scale biomass gasification for electricity generation*. The feasibility of various future scenarios will be evaluated in order to know what is the likelihood for the technology to become competitive in the short term.

2 ANALYTICAL FRAMEWORK

The aim of this chapter is to outline the theoretical framework that will be used later for the analysis of biomass gasification learning process. The development and diffusion process of a new technology, also known as technical change, is something that has been studied from very different points of view. These, have generally been classified into two categories, namely “demand pull” and “technology push” (Dosi 1982) based on the dependence of the innovation from changes in the economic environment, i.e. the demand.

However, these interpretations present a rather crude conception of technical change missing some important features of the process. On the one hand, demand-pull approaches states that the technical change is fully conditioned by the market, without defining the why and when of certain technological developments. On the other hand, the technology-push theories fail in defining the several-feedbacks between the economical environment and the technical change. Nevertheless, it is accepted by both interpretations that technical change is a long uncertain and painful process (Bergek 2008). Thus, it requires a complex analysis to understand its current structure and trace the dynamics. In order not to miss any fundamental aspects, it needs to be tackled in a non linear way.

Some non linear models have been proposed to study the innovation process and, in all of them, it is remarkable the importance given to the research and the knowledge base. One of the most well-known is the so-called *chain-linked model of innovation* (Kline 1986). It presents a system made up of five linear interconnected paths in the process of innovation. Such paths connect three main sub-processes: The research, the knowledge base and the central chain of the technology innovation process. The following *Figure 2-1* is an illustration of the model.

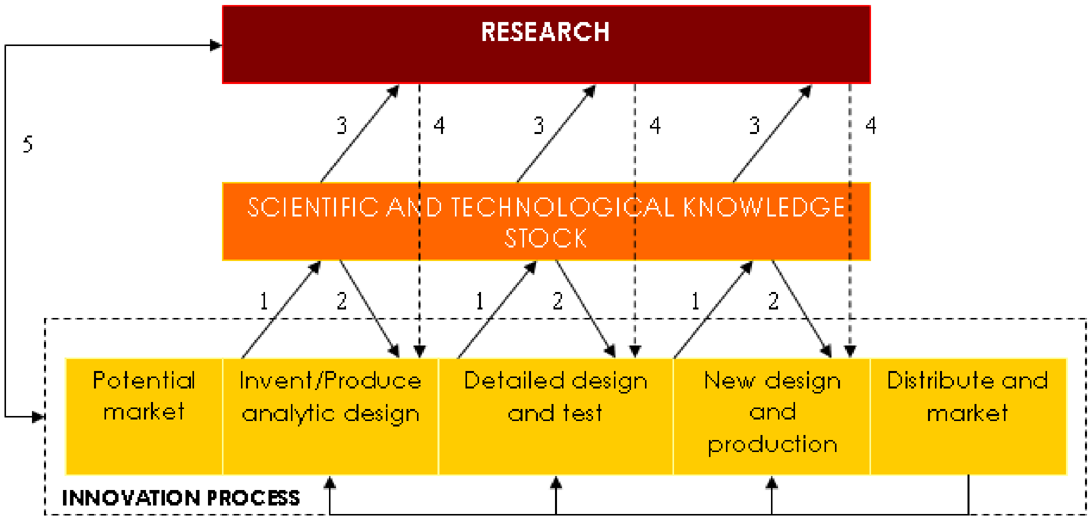


Figure 2-1. Illustration of the chain-linked model of innovation

The first and the second paths refer to the classical innovation process, where an idea is materialized in an analytic design that must fit a certain market requirement, and its feedback-links. The third path is made up of the link between knowledge and research. When there is a problem in the central chain, the knowledge base is used (arrow 1). If it contains enough knowledge, the information is transferred to the analytic design (arrow 2). If there is not enough knowledge to solve the problem, it will be necessary to research (arrow 3). The results of this research process will be added to the knowledge stock and subsequently to the design (arrow 4). The fourth path is the connection between research and invention. In some occasions, new scientific discoveries allow revolutionary innovations (suggested previously by the technology push linear models). In addition, the perception of new needs can also stimulate research.

As we can see, the depth of the knowledge base and the intensity in research activities are key points in the global innovation process. Hence, the decision for undertaking a deep study of these two aspects is strongly justified.

The formerly presented theoretical models allow a better understanding of the connections between the system components, but it is still difficult to use them as a tool for the analysis of the innovation process. This is one of the reasons why different approaches have been developed in order to facilitate this analysis. One of these is the so-called Innovation Systems Approach.

2.1 Technology Innovation Systems Approach

A large number of researchers from different fields claim that the technological development can not be viewed as an isolated phenomenon but has to be studied as a part of a system, the "innovation system". This system has been defined by (Carlsson 1995) as "*… network or networks of agents interacting in a specific technology area under a particular institutional infrastructure to generate diffuse and utilize technology"*. Four different main approaches have emerged for the study of this system (Johnson 2001): the national systems approach (Edquist 1997), the technological system approaches , the sociotechnical system approach (Bijker 1995) and the network approach (Håkansson 1990).

There are several differences between these approaches which make it difficult to compare and combine their findings. It is necessary to see if there is any agreement between the approaches and what they claim. This is why the concept of function is used. The concept is understood as *the contribution of a component or a set of components to the goal* (Johnson 2001).In this case the goal is the development, diffusion and use of new technologies.

A synthesis and further development of the functions proposed by the different approaches have been undertaken (Bergek 2008).Seven different functions have been selected representing all the contributions made by the different system components.

As an attempt to give the reader an overview of the magnitude of an innovation system, the seven functions are listed below with a brief explanation for each of them.

1. *Knowledge development and diffusion*. The breadth and depth of the knowledge base and how well knowledge is diffused and combined in the system.
2. *Influence on the direction of search*. The combined strength of incentives and/or pressures for the organizations to be induced to enter in the system
3. *Entrepreneurial experimentation*. Probing into new technologies and applications and the social learning process unfold
4. *Market formation*. Types of markets formed considering *nursing* markets, *bridging* markets and *mature* markets
5. *Legitimation*. Social acceptance and compliance with relevant institutions
6. Resource mobilization. Capability of mobilization of competence/human capital, financial capital and complementary assets.

7. *Development of positive externalities*. Formation of positive external economies (or free utilities).

Nevertheless, the entire analysis of the BMG technology innovation system is beyond the scope of this thesis. The analysis carried out in this report will focus on the part of the system related with research activity and the knowledge base. There are two functions that match with those two. These are *knowledge development and diffusion* and *entrepreneurial experimentation*. In the next section a deep description of both is presented.

2.2 Knowledge development and diffusion

Knowledge is considered the base of the innovation system and two levels of it can be distinguished. The first level is related with opportunities of initial innovations from university-scientific breakthroughs or, at the same level, with technologies in research centers. The secondary level is the knowledge of suppliers that can contribute with their own experience in the sector or in other case, knowledge from the user demands (Malerba 1999). Concerning diffusion, knowledge is not easy to be extended and it can be more or less accessible for firms, depending on their role or network they belong to. In that sense, networks allow the sharing of internal knowledge and it is freely accessible within the actors. By contrary, the external knowledge is not directly obtained and new connections with other firms have to be done .

In this context, different types of knowledge can be distinguished in the Innovation System, e.g. scientific, technological, production, market, logistics and design knowledge (Bergek 2008). Despite of that, this thesis seeks to focus on scientific and technological knowledge, which play a crucial role in the learning process. Moreover, rapid scientific advances and technological innovations are ever enhancing the most advanced knowledge economies (Hamel 2005).

According to Johnson (2001) in his national systems of innovation approach, there are several sources of new knowledge. On one hand, some of them are related with efforts in *R&D activities* and day by day activities (i.e. *learning-by-doing* and *learning-by-using*). On the other hand, frequently, bottlenecks and failures make difficult obtaining solutions and stating also the problem definition, but sometimes they might create new ideas (i.e. *learning by failing*).

This new acquired knowledge will be combined with the previous acquired one to develop solutions for new technological problems. Thus, the learning process is continuously regenerated with cumulative knowledge, and new research questions always arise, as we can see in the *Figure 2-2*. Some other authors support that knowledge may also be acquired by imitation, both among actors and coming from other technologies. (Jonhson, 2001).

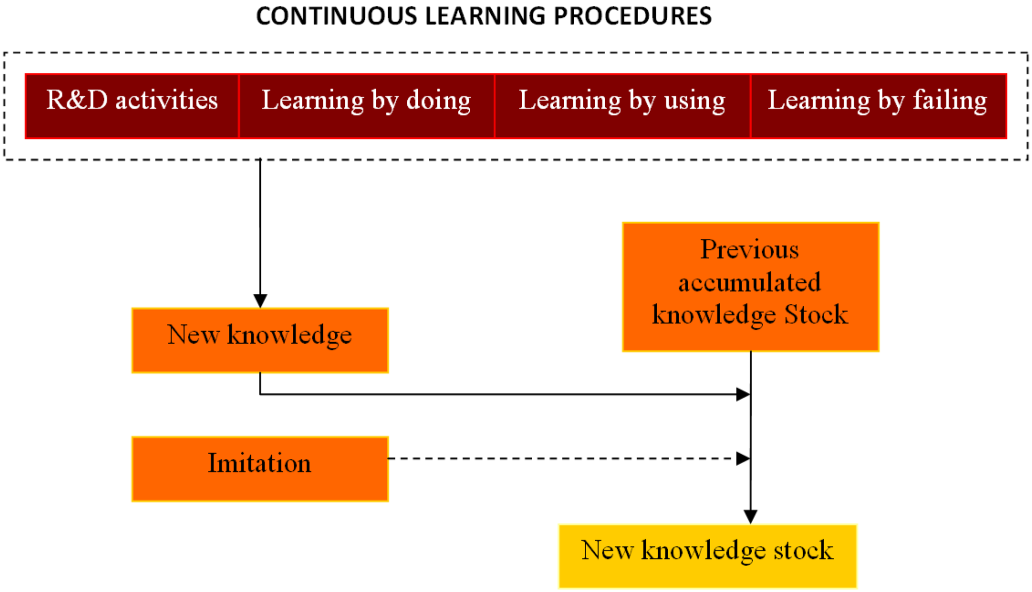


Figure 2-2. Sources of new knowledge

Following this, not all the countries have the same opportunity to generate new knowledge and some factors influence on it. Factors like the level of knowledge from universities, networks, particular interactions, users and firm efforts, enhance the ability to create. In addition, the quality of the relationship among actors has also an important influence in generating new knowledge (Nelson 1993).

Finally, this function can be measured by some indicators which are explained in the work procedure section. One of the most used is the learning curve, which receive special attention in this thesis. For this reason, an additional section introducing the learning curves framework is presented in this chapter.

2.3 Entrepreneurial experimentation

Technological change is characterized by a high degree of uncertainty (Rosenberg 1996), which condition the diffusion process of new growing technologies. Furthermore, due to the great uncertainties attached to the innovation process, innovation firms have experimented high failure rates.

Uncertainty comes from different sources and it presents several different characteristics that shape the innovation process and its influence to the economy. One of the aspects of the innovation process that is seriously affected is the entrepreneurial learning. The uncertainties that entrepreneurs perceive will affect their innovating decisions and can prevent them from engaging innovating projects (Meijer 2007). However, at the same time entrepreneurial learning activity has also been considered one of the main sources of uncertainty reduction (Kemp 1997) since every time an entrepreneurial project succeed a social learning process will unfold.

This learning process has historically been classified in two different modes according to the way of obtaining new knowledge; the exploitation of old certainties (utilizing previous skills and knowledge) and exploration of new possibilities (probing new technologies and applications) (Schumpeter 1934). The latter mode is the so-called *entrepreneurial experimentation* and it is connected with the third function described above in the TIS approach framework.

Entrepreneurial experimentation is important along the whole innovation process and specially in the early stages, when knowledge is changing very rapidly, uncertainty is very high and barriers to entry very low. Hence, new firms are the major innovators and are the key elements in industrial dynamics (Malerba, 1999). The existence of these pioneer entrepreneurs that decide to look for new knowledge through experimentation is strongly necessary for the global learning process. Once they find an individual business opportunity, they cooperate in order to benefit from complementary specialization. Even if the commercial results of the experimentation are not successful, it will promote the formation of new entrant firms, support institutions and develop organizational and market capabilities (Breshanan 2001).

2.4 Learning curves

As it has been told previously, learning is one of the most important sources of technical change and innovation. Different learning methods, such as learning by using, learning by failing or learning by doing have been presented. Measuring the combined effect of them on technical change would provide a powerful tool for the analysis of the innovation process. Hence, this is the primary aim of the learning curve concept.

Initially, it was introduced to the aircraft industry in 1936 by T. P. Wright as an attempt to describe a basic theory for *obtaining cost estimates based on repetitive production* of airplane assemblies. Since then, learning curves have been applied to all types of work.

The theory is based on the fact that the effort or time expended on an operation decreases by repeating the task. Numerically, the initial hypothesis was that *the man-hours required to complete a unit of production will decrease by a constant percentage each time the production quantity is doubled* (Wright 1936). This is what we call the *learning-by-doing* pattern.

In the energy technology context, the technical change is measured as cost improvement of production as a result of a learning process, expressed as a function of experience gained from an increase in its cumulative capacity or output (Jamasb 2007).

Nevertheless, these cost reductions reflect not only the benefits from learning-by-doing at existing facilities that install technologies, but also the benefits derived from investments in research, development and demonstration that produce new knowledge and new generations of a technology.

Ideally, the learning curve equation would explicitly include the effects of additional factors like RD&D expenditures. However, such relationships are extremely difficult to develop and validate because of data limitations (Rubin 2004). In the following *Figure 2-3* (Watanabe 1999) some different factors that influence the total cost are shown.

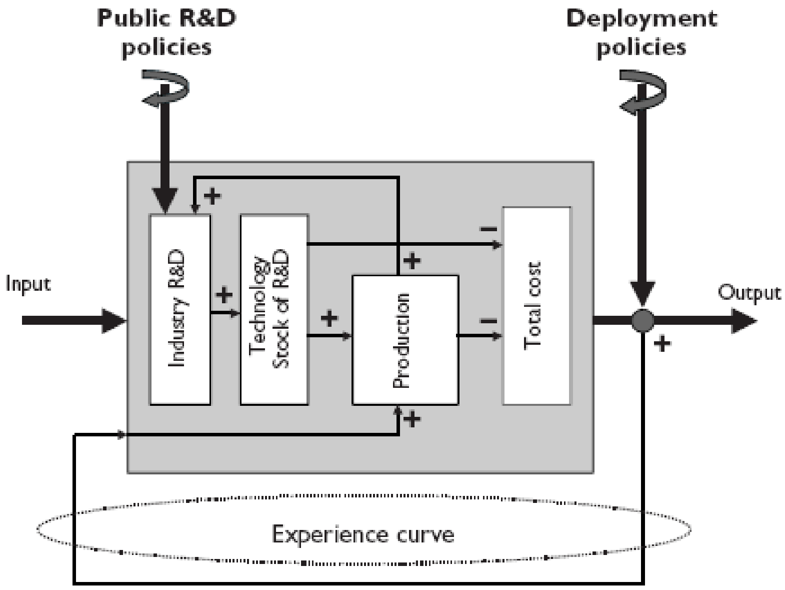


Figure 2-3. Factors affecting the production cost.
Source: Watanabe, 1999

As it can be see, the learning curve (here termed experience curve) is affected by the combination of other factors a part from the experience gained in the production stages.

Thus, the single-factor model presented below is commonly used. It presents the cumulative capacity as a surrogate for total accumulated knowledge gained from many different activities whose individual contributions cannot be readily discerned or modelled (Rubin 2004).

$$C = a \cdot N^{-b}$$

In this expression C is the electricity production cost, N is the total cumulative installed capacity and a and b are constants that model the cost reduction.

This model states that the cost tends to decrease as technology evolves through the different stages (Rogner 1998). First stages are characterized by high production costs due to small batch production modes based on manual operation, highly diversified machinery and low volume purchases of goods and services. Afterwards, when technology gets closer to the maturity stage there is a decrease of the labour intensity with more standardized, mechanized and automated operation that lead to lower production costs. Thus, the curve adopts the following shape shown in *Figure 2-4*.

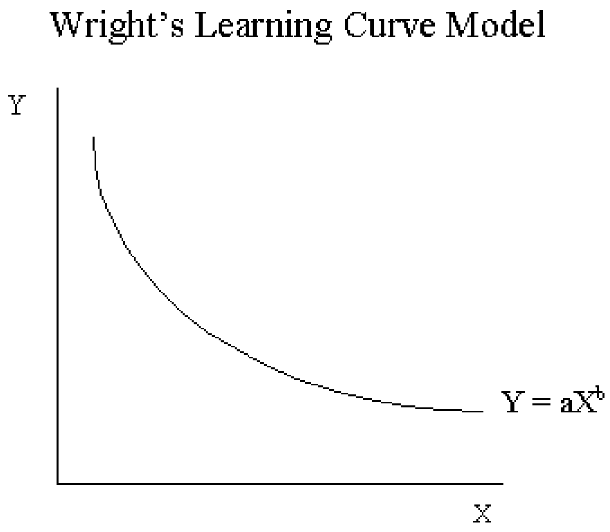


Figure 2-4. Typical shape of a learning curve.
Source: Management And Accounting Web, http://maaw.info/LearningCurveSummary.htm

2.5 The learning rate

In the model introduced previously, the effect of b can be understand as "*the percentage cost reduction for each doubling of the cumulative installed capacity*" (Rubin 2004). This is, precisely, the definition of the learning rate (L), which can be formulated as:

$$-b = \frac{\log L}{\log 2}$$

Hence, the learning rate is directly obtained from the value of b, as it can be seen in the following *Table 2-1*.

Table 2-1. Examples of learning rates related to different values of the constant b

A value of b of	Learning rate (L)
0,1	7%
0,2	13%
0,3	19%
0,4	24%
0,5	29%

The literature on learning curves frequently summarizes observations in terms of this single parameter (Jamasb 2007) since it is a worthy tool to compare the performance of different technologies in various periods, as it can be seen in the **¡Error! No se encuentra el origen de la referencia.**, given in Appendix A.

The great majority of published learning rate estimates relate to electricity generation technologies (Jamasb 2007).

This learning rate literature has led, in some cases, to the use of a general “rule of thumb” learning rates of 20% coming from the observed rates for many electricity generation technologies. However, there is evidence on the decrease of learning rates over time that suggest that this rule may be too much optimistic when modeling long-run periods. One of the aims of this thesis will be getting to know the technical advances required to reach a specific learning rate. This will give the chance to assess the realism of the currently used learning rates.

3 METHODOLOGY

This chapter describes the methodology followed to analyze and assess the two IS functions proposed in the Framework section: *Knowledge development and diffusion, and Entrepreneurial experimentation*. *Figure 3-1* shows the different analytical steps of this study and the main considered points.

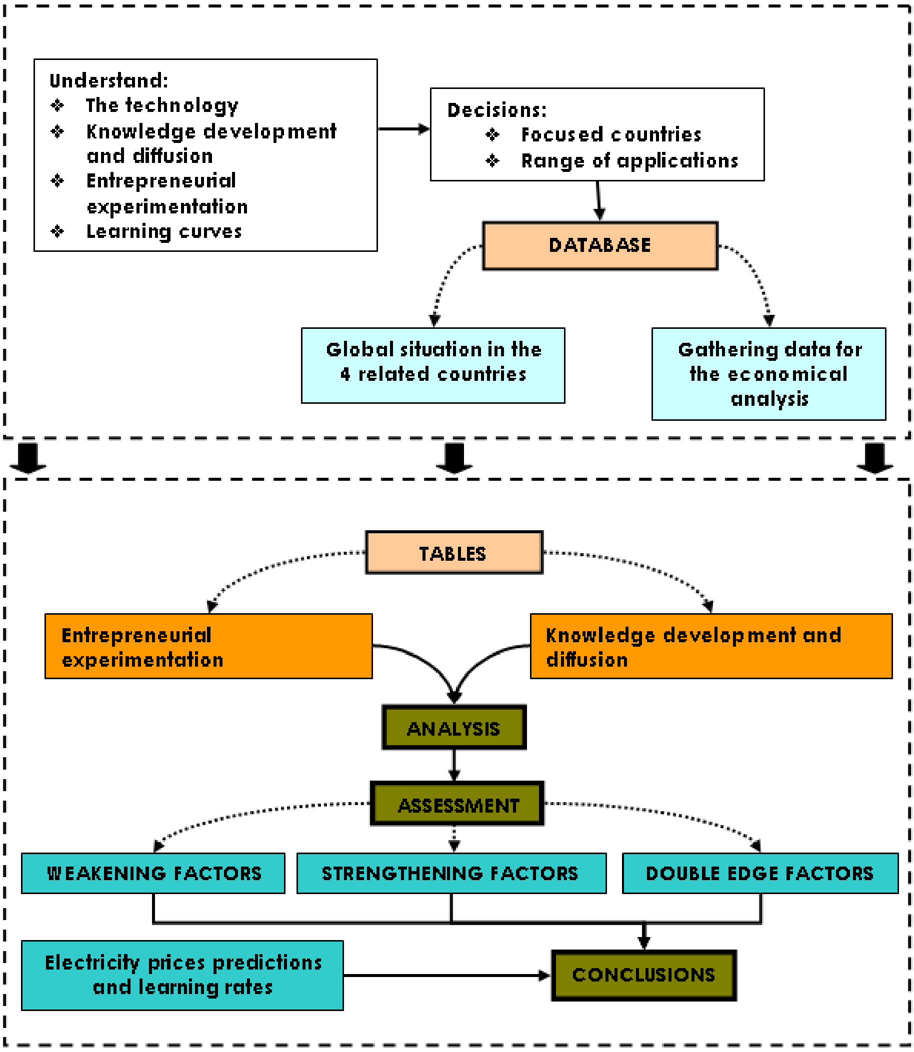


Figure 3-1. Methodology scheme

As a starting point, the first contact with biomass gasification was through different articles about the TIS (Technological Innovation System) and different technical aspects of the gasification technology. It is important to point out the article “Status of Biomass Gasification in the countries participating in the IEA Bioenergy Task 33 Biomass Gasification and EU Gasnet" (Kwant 2004). This article gives good insights to find BMG projects and plants since 1970 in the whole Europe. Moreover, another important reference is: "Handbook Biomass Gasification" (Knoef 2005). This book allows clarifying certain technological concepts and additionally, it is a complement to the first mentioned article. Once the technical concepts were understood, an intensive research was made on learning curves. The main reference is the article: "Techno-Economic Assessment on the Gasification of Biomass on the Large for Heat and Power Production" (Bòlhar 2004). All this previous study triggered the preparation of a database taking into consideration the one created by Hans Hellsmark. Starting from this database, an in-depth country analysis was made in four specific countries: Sweden, Finland, Germany and Austria. Their potential technology development, concerning BMG, and the advice from our supervisor were the main reasons for this choice. Moreover, this research analysis was focused on the whole range of applications but only considering the most important existing projects and plants. Thus, the database allowed connecting plants, actors, technologies, year of establishment and other technical aspects. All this information comes from different scientific articles, web pages and books, particularly, the two references initially mentioned. It is essential not only for the next functions analysis, but also for the initial data requirements in the economical assessment explained later on.

Using the database, different graphics were plotted to explain the global situation in the 4 related countries. Thus, the principle trends concerning applications and technology started arising, but it was not enough information for assessing the performance of the two considered functions. Hence, an in-depth analysis of the four related countries was necessary for obtaining further assessments.

3.1 Analysis

Once a solid knowledge base was gathered, an in-depth analysis was carried out for the two IS functions. In order to do so, several questions were established, following the article "Analyzing the Functional Dynamics of Technological Innovation Systems: A Scheme of Analysis" (Bergek, 2008). Consequently, different tables were made to answer these questions. These tables consist of two groups, one for each function. In the case of *Entrepreneurial experimentation,* tables were focused on the connection between entrepreneur and experimentation, taking into consideration the actors' origin and the technological character of the experiments. However, *knowledge development and diffusion* tables were centralized on the R&D project itself, looking not only for the international and national influences and its diffusion; but also for the private and public knowledge contribution. Moreover, an additional table was created in order to assess the continuity of the identified projects, ordering chronologically the knowledge transference among pilot, demonstration and commercial plants. To gather and analyse all this information, several national reports were taken into account as it is shown in *Figure 3-2*.

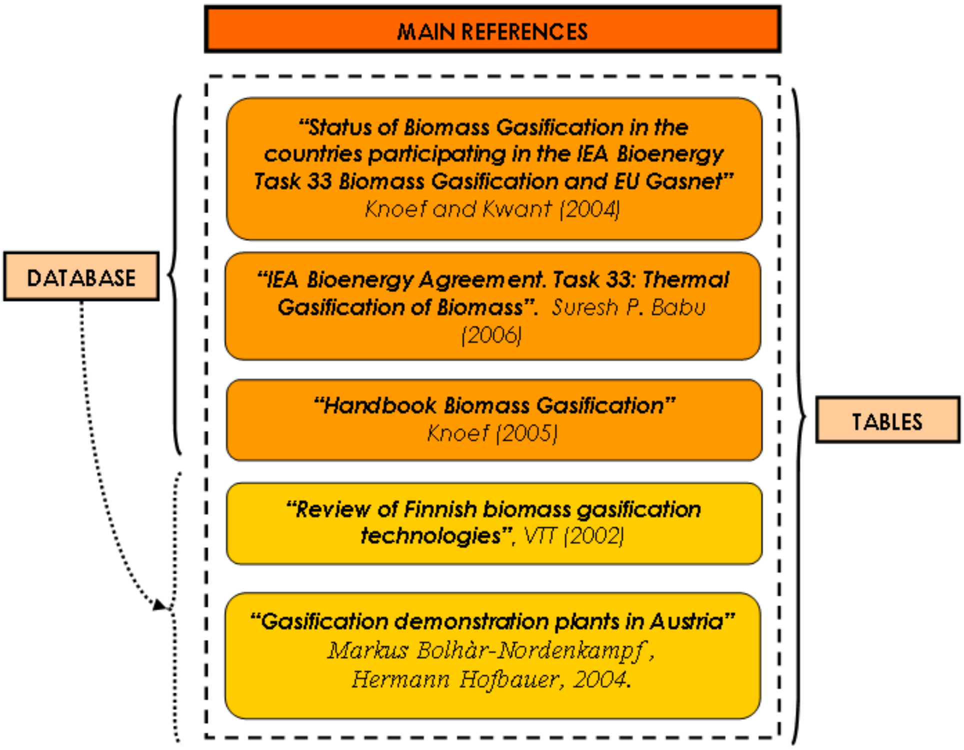


Figure 3-2. Main references

In the case of Germany and Sweden, the breadth of R&D activities and the large number of plants simplifyed the research. Therefore, for ensuring a wide and good knowledge level of both countries, only few references were considered as shown in *Figure 3-2*.

Then, the database and the acquired knowledge allow analysing and assessing the two particular functions in each country and to compare their development trends. This comparison between countries enhanced a more accurate analysis due to the strong influences between each other.

3.2 Electricity prices and learning rates methodology

One of the aims of this thesis was to assess numerically the knowledge development of one of the most common applications of BMG, the small scale power production. In order to do it, two main indicators have been used; firstly, the price at the electricity produced must be sold in order to make the plants profitable, and secondly, the learning rate, which has been explained in the framework section. The values of these two parameters have been calculated through the methodology described below. The following *Figure 3-3* gives a brief explanation of the main steps of this methodology.

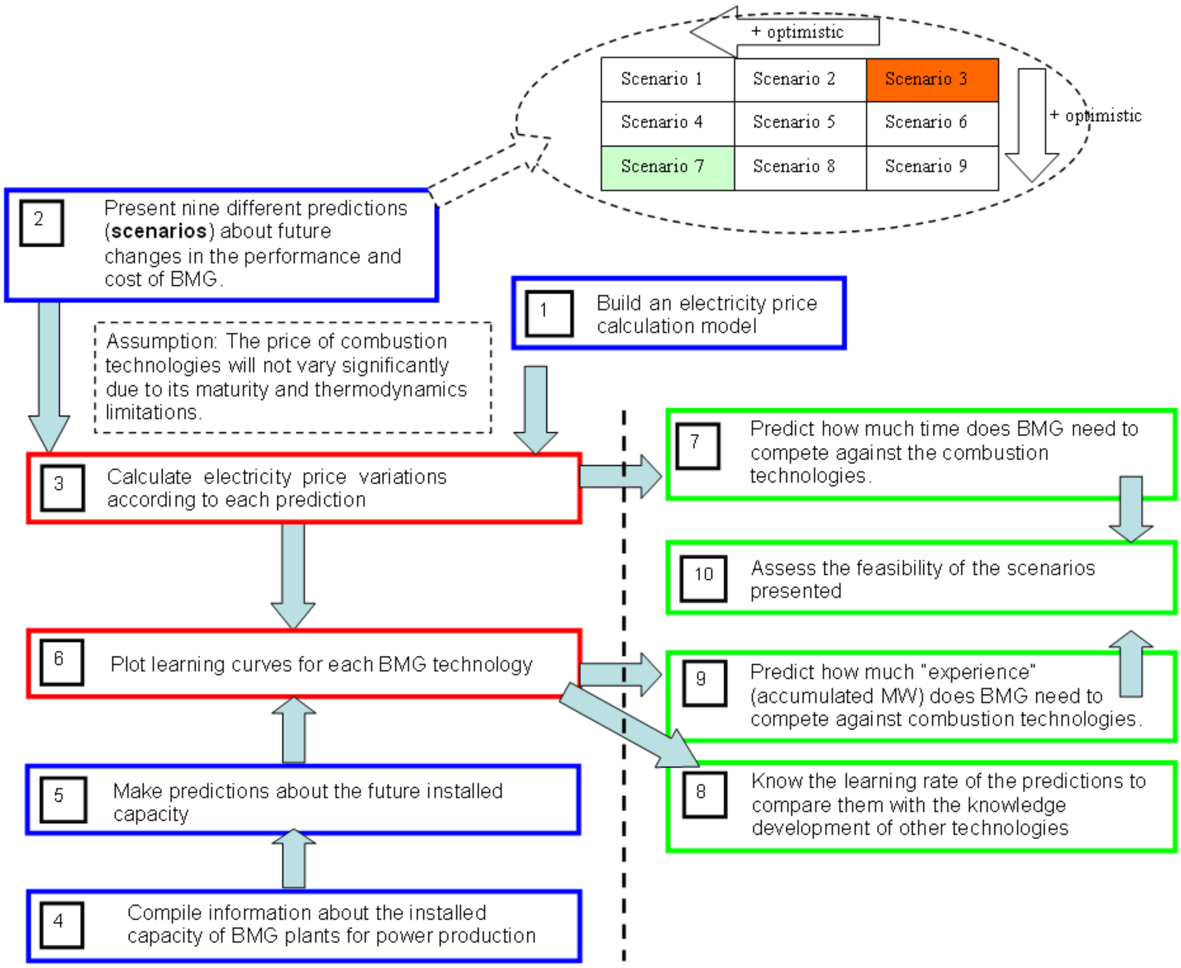


Figure 3-3. Main steps of the methodology followed to obtain electricity prices and learning rates

The first step is building a numerical model of a small scale gasification system (step 1), which is presented in detail in the next section of this chapter. This model is designed in order to calculate the price at the electricity must be sold in order to guarantee the profitability of the plant, which is the main output. This model will also be used to calculate the electricity price of a biomass combustion based system for further comparisons.

At the same time, predictions about the future evolution of some of the input parameters considered in the previous model are made (step 2), giving the opportunity to evaluate the technical feasibility of various different future scenarios. The predictions are then evaluated within the model (step 3) to obtain the prediction of electricity prices. Comparing the obtained results it is possible to foresee the time needed by BMG to reach the same electricity prices as combustion based technologies (step 7).

On the other hand, the information collected (step 4) in the database, with the power input size and year of commissioning of the main gasification plants for power production of the four studied countries, is used to predict the future installed capacity (step 5). Using both presented predictions (electricity price and installed capacity), learning curves can be plotted obtaining the rate of learning (step 6). This information can be used to compare the knowledge development of BMG with other renewal technologies through the learning rates (step 8) as well as to predict how much experience, in terms of installed capacity, BMG needs to reach combustion electricity prices (step 9). Finally, by analyzing the results obtained from steps 7 and 9, it is possible to assess the viability of the scenarios presented in the step 2 by comparing the predicted results with the technical requirements.

Electricity price calculation model

The following section introduces the mathematical model (*Figure 3-4*) used for the electricity price calculation. The model[1] is based on a more complex model developed by the University of California. The gasification system is composed of two main parts; the gasification part, including gas cleaning and fuel feeding components, and the power generation part, where the clean gas is used to produce electricity using a prime mover.

In the case of the combustion-based systems, the first part consists of the combustion boiler that will be used to create the steam used in the second system part by the steam turbine.

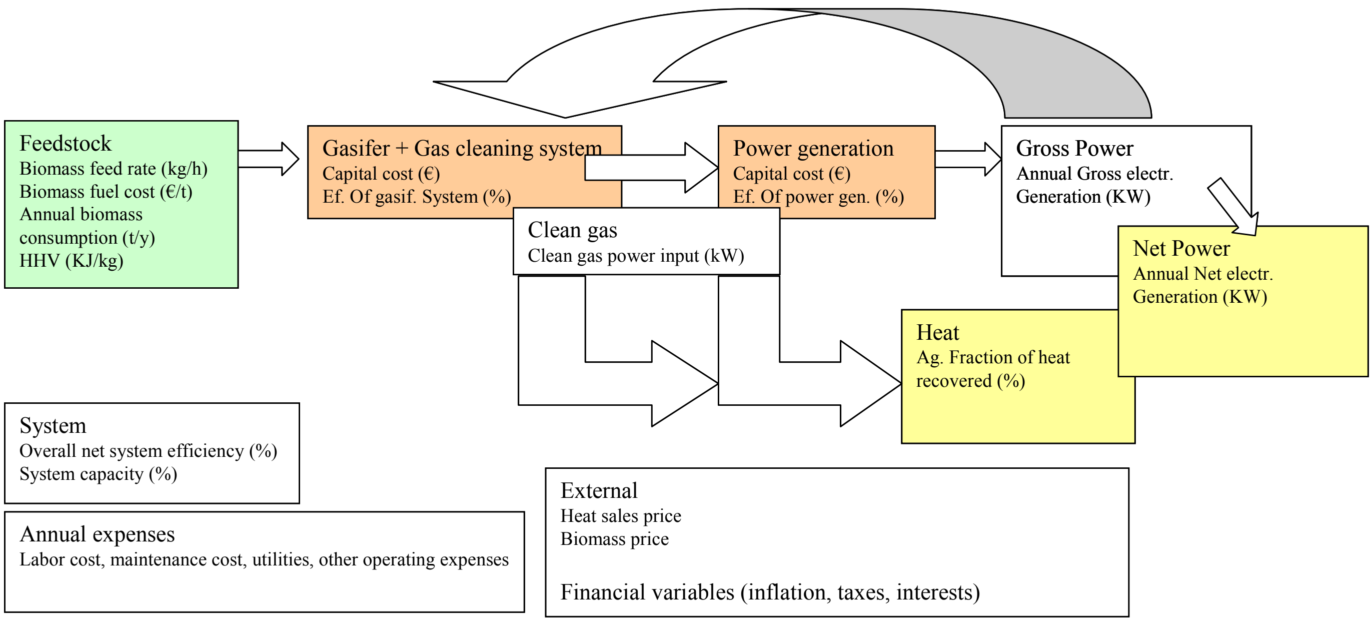


Figure 3-4. Diagram of the simplified gasification model

Both system parts are characterized by its capital costs, which will vary depending on the future predictions used in each of the scenarios presented above, and on its efficiency. The efficiency of the gasification system is defined as the high heating value (HHV) of the clean gas divided by the HHV of the biomass feedstock and the gross efficiency of the power generation system is defined as the fraction of produced electrical power referred to the clean gas power entering the prime mover. Since part of the power produced is used in the own system, a gross and a net electrical power output have

[1] http://faculty.engineering.ucdavis.edu/jenkins/CBC/Calculator/index.html

been defined. The difference between the gross electrical energy at the output and the fuel power input is the energy lost, which will be partially recovered by the heat recovery system.

For the economical evaluation of the simulated concepts (*Table 3-1*), the interest rate has been calculated on a cash flow basis, considering an amortization period of 13 years for the plants and a utilization period of 20 years.

Table 3-1. Economical evaluation basis used for the electricity price calculation

Evaluation basis
Period of amortization: 13 years
Period of utilization: 20 years
Interest rates: 6,5% (debt), 11,5% (equity)
Tax rate: 40,34%
Inflation rate: 2%
Capital structure: 45% equity, 55% debt
Capacity factor: 85% (7446 h/y)
Heat recovered: 50%
CHP operation heat sales: 0,0095 €/kWh$_{th}$
Biomass feedstock costs: 13,59 €/t
HHV:19400 KJ/kg (demolition waste wood)
Staff cost: 0,16 c€/year.kW$_{net\text{-}el}$
Maintenance cost: 0,03 c€/year.kW$_{net\text{-}el}$
Residues treatment: 0,02 c€/year.kW$_{net\text{-}el}$
Insurance: 0,01 c€/year.kW$_{net\text{-}el}$
Utilities, management and other operating expenses: 0,03 c€/year.kW$_{net\text{-}el}$

Regarding the capital costs related to the financing of a new plant, it has been considered that the plant is both financed by equity (45%), i.e. capital coming from private investors, and long-term bank debt (55%), as a typical capital structure for a utility company[2]. The debt interest rate (6,5%), the cost of equity (11,5%) and the combined tax rate (49,34%) have been selected according to similar economical assessments[3]. It has also been fixed an inflation tax rate of 2% affecting the biomass fuel price and the heat sales price. The capacity factor has been assumed to be of 85%, i.e. 7446 full load operation hours, which is the common value taken when plants are designed (Bòlhar 2004). An efficiency of 50% have been assumed for the heat recovery system, selling heat at 0,0095 €/kWh$_{th}$. A mix of demolition waste wood has been evaluated as fuel with a HHV of 19400 KJ/kg and a price of 13,59 €/t. The direct yearly operating costs have been calculated as a function of the installed capacity. These include the salary of labourers, the maintenance of the system components and the treatment of the residues generated by the plant such as tars and ashes. An accident insurance as well as other indirect operating expenses, such as the utilities of the plant, have also been considered.

[2] http://belfercenter.ksg.harvard.edu/files/igcc%20financing%20chapter%205.pdf
[3] http://www.ecn.nl/phyllis/single.html

3.3 Factors

Once the two mentioned functions are analysed and the economical study is established. All the countries' factors were put together aiming to evaluate the global influence over knowledge development and diffusion, and entrepreneurial experimentation. This assessment allowed identifying the main factors affecting these four countries, distinguishing between weakening, strengthening and double-edge factors. Finally, this thesis ends establishing a discussion and conclusions, answering the research questions and fulfilling the purpose initially proposed.

4 TECHNOLOGY BACKGROUND

This section reviews the existing technologies to gasify biomass. There are some similarities between combusting and gasifying biomass and the experience acquired from the first technology have been used in gasification. As it is exhibited in *Figure 4-1*, there are some differences between them. Firstly, the obtained gas is treated before the gas utilization entrance and next, the used prime movers are different.

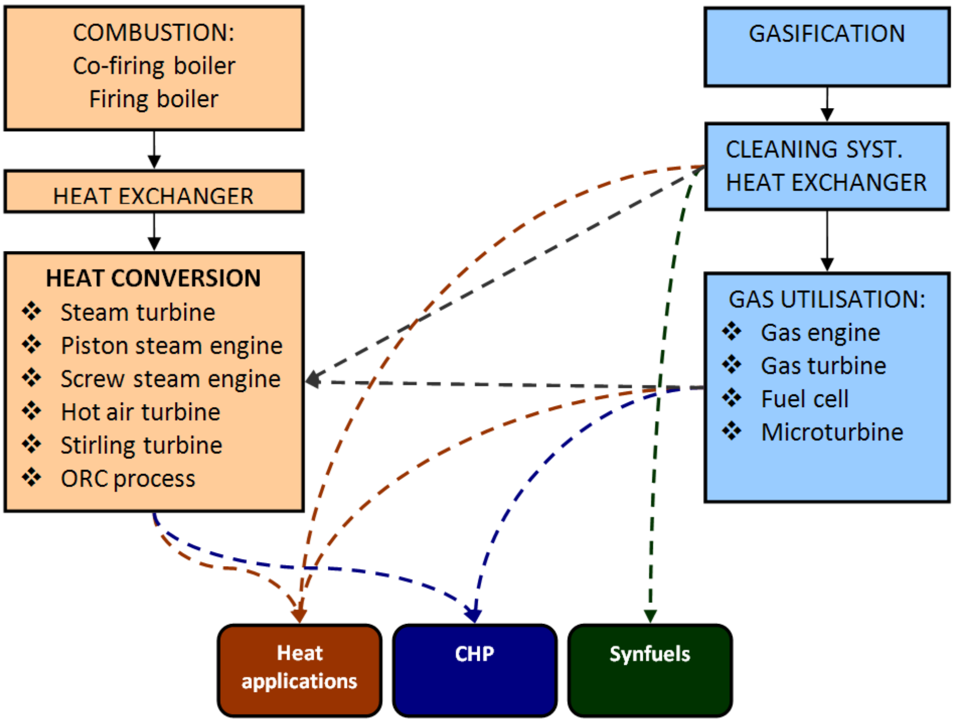


Figure 4-1. Comparison between gasification and combustion processes
Source: (Bolhàr, 2004)

Synfuel production is considered as a potential application of gasification. Moreover, gasification provides a higher efficiency and achieves fewer contaminant emissions due to small gas flows (Bolhár 2004).

Apart from that and before analyzing the two related functions, it is necessary to have a brief overview of the BMG history in order to address the historical facts that influenced the development of this technology. Afterwards, a technological description of the main components in the BMG system is described.

4.1 Historical background

The gasification process was initially developed in 1792 to produce "town gas" from coal, using it mainlyfor lighting. Afterwards, it was put into practice in London during the 1850's, providing light to almost all this city. Currently, this type of fossil gasification presents an important variety of applications, producing electricity, hydrogen, and other valuable energy products. Several electric power plants are now operating commercially in the whole world but the environmental concerns and the lack of this type of source claims the use of biomass. It is considered that the historical development of biomass gasification started during the WWII even though, important breakthroughs arose before that date. During this military conflict, some entrepreneurs started using gasifiers to drive different types of transportation in Europe. Moreover, this technology tried to find a niche market but the difficulties in that moment made it necessary to wait for better times. In 1973, the oil crisis was essential for encouraging the usage of BMG (Knoef 2005). The price of fossil fuels increased dramatically and the world became aware of its dependence, demanding the use of renewable energies, such as biomass (Kwant 2004). Moreover and during the 1990's, the Kyoto protocol was adopted to prevent climate change, creating major awareness of the greenhouse gases emission. Due to this environmental concern, several financial grants were given to a variety of R&D projects concerning BMG and the first demonstration and commercial plants were established around the world. As it is known, the interest in BMG has suffered important changes and the number of failures during the history has created certain doubts about this technology. For that reason, gasification has sometimes got bad reputation and the availability of grants has been, somehow, reduced. Thus, multiple historical facts have influenced negatively and positively on BMG but the willingness to develop this promising technology is overcoming all of them over the years.

4.2 Technology background

Before describing the landscape of this technology in the four considered countries, it is essential to explain the main features of the BMG system components. Four main parts can be identified in the current state of biomass gasification technology: Feeding system, gasifier, gas cleaning system and the prime mover. The range of these components can be spitted up into different groups and several associations of each one can be made for a specific application. Thus, an overview of the main problems, solutions, advantages and drawbacks of each part is reviewed in this section.

4.2.1 Feedstock and pre-treatment

The use of biomass feedstock has suffered a significant increase after the first world oil crisis in 1973 (Overend 2003). Since then, several pilot and demonstration plants have had problems in the feeding system and numerous R&D activities have been conducted to improve it. Moreover, the feedstock size is an important detailed feature in this type of plants and it varies depending on the other system components, even though it is usually related to gasifiers. A large number of biomass materials can be distinguished, such as wood chips, cleaned wood, bark, demolition wood, waste, demolition lumber, sewage sludge, refuse derived fuel (RDF), etc. These resources have to be treated at a specific level, depending on the system requirements but the feeding treatment is always necessary for obtaining the expected gas quality (Knoef 2005).

Concerning solid waste, some gasification processes have been developed as an alternative to incineration. A basic need in waste gasification systems is the use of specific cleaning devices due to the high content of contaminants in the produced gas. Thus, the use of pure waste is not common and it is usually combined with fossil fuels. Apart from that, black liquor is another important fuel, by-produced in pulp and paper industries. This by-product is a mixture of different chemical components and it also is based on a recovery system. This explains the large number of R&D activities aimed to replace the conventional recovery boiler into a new technology. The most important characteristic of this fuel is its potential for generating electricity and heat production but even so, it is addressed under combustion technologies (Marklund 2001).

As it was mentioned before, the feeding system for BMG is related to the type of reactor (Knoef 2005). Thus, Fixed and Fluidized bed gasifiers have experienced different failures due to the feeding requirements. The most typical problems are related to bridge formation, sealing and foreign materials in the biomass fuel. Some other failures are related to changes in the fuel composition or high pressures. Hence, the feedstock and fuel feeding has been an essential concept for the BMG evolution and it is currently under development.

4.2.2 Gasifier

Reactors can be considered the main part of the gasification system and over the years, most R&D activities have been focused on this technology. There are three general types of gasifiers: Fixed bed, Fluidized bed and Entrained flow. Firstly, Fixed bed reactors can be associated with the direction of the gas flow, calling them updraft, downdraft and cross-draft (Knoef 2005). In the case of Fluidized bed, the gasifiers are characterized by the fuel suspension behaved as a fluid. This suspension can be small (bubbling) or high (circulating). Finally, Entrained flow gasifiers are fed with pulverized solid or liquid fuel in the co-current flow direction. All these reactors have advantages and drawbacks that encourage or discourage entrepreneurial decisions, all exhibited in *Table 4-1*.

Table 4-1. Advantages and drawbacks of different gasifier reactors
Source: Knoef, 2005

Gasifiers	Advantages	Drawbacks
Fixed bed Updraft	❖ High simplicity ❖ High charcoal burn-out ❖ High gas efficiency ❖ Use fuels with higher moisture content ❖ Accepts fuel size variation	❖ High amount of tar and pyrolysis products ❖ Extensive gas cleaning required in power applications
Fixed bed downdraft	❖ Lowest levels of tar ❖ Best option for gas engines ❖ At low load levels, less particles in the gas	❖ Limited scale up ❖ At low temperatures, more quantity of tar produced ❖ High amount of ash and dust particles ❖ Strict requirements in fuels
Fixed bed downdraft: multistage	❖ Decrease tar production ❖ Optimization of each zone	❖ Major complexity in the design
Fixed bed crossdraft	❖ Fitted in very small scale operations ❖ Due to the high temperatures, less requirements in gas cleaning	❖ Minimal tar converting capability
Atmospheric Fluidized bed	❖ Compact construction ❖ Low and uniform temperature profile ❖ Accepts fuel size variation ❖ Ash melting points allowed	❖ High tar and dust content ❖ Alkali metals at high temperatures ❖ Complexity in the air supply and solid fuel ❖ Power consumption
Pressurized Fluidized bed	❖ Low level of power consumption ❖ Higher methane content ❖ Compact, low investment costs ❖ Sintering ash	❖ Complex fuel feeding ❖ Cleaning problems ❖ Complexity of installations ❖ High specific investments in low capacity installations
Entrained flow	❖ Able to large capacities ❖ Short residence time	❖ High investments ❖ Strict fuel requirements

As it is seen, all gasifiers have drawbacks that can derive to failures but depending on the focused application, the problem can be more of less important. Most important disadvantages are related to gas cleaning and it is always a big deal for entrepreneurs. Some others concern to feeding problems and complexity of the reactor, also important points to take into consideration for R&D activities.

Moreover, the standardization of this technology is not well defined and the possibilities between gasifiers and scale are quite extensive. Concerning CHP applications, the scale range can be split up into four different measures, as it is seen in *Table 4-2.*

Table 4-2. Size range of CHP plants in biomass gasification
Source: VTT, 2006

Scale range	Gasifier
Small scale	$< 500\ kW_{el}$ & $1\ MW_{heat}$
Medium scale	$(0.5 – 15\ MW_{el})$ & $(1 – 15\ MW_{heat})$
Large scale	$(15 – 150\ MW_{el})$ & $(15 – 150\ MW_{heat})$
Co-fired plants	$> 50\ MW_{fuel}$

In the case of small scale plants, downdraft is the most typical reactor used. By contrast, Updraft gasifiers are more focused on heat applications at small to medium scale. Regarding medium scale CHP applications, different gasifiers are able for this size, such as modified updrafts, fluidized bed and multistage processes. Scaling up, large scale applications are associated with pressurized fluidized bed gasification processes, with circulating (CFB) and bubbling (BFB) fluid suspension. Additionally, coal firing boiler is often combined with fluidized bed gasifiers, more specifically with CFB.

4.2.3 Gas cleaning

As it is mentioned in the last section, the gas cleaning system is a complex technology that benefits the gasification process, enhancing the gas quality for a better efficiency and performance. This technology needs to be improved very often but the strict requirements from gasification technologies, plant size and gas utilization, makes its evolution highly difficult. Sometimes the main problem is related to the temperature because if it is too low, some impurities appear in the gas. The biomass gas contains different types of contaminants but the most risky ones are tars and particles. Tars cause catalyst in the system, so syngas and gas engines are extremely affected in that sense. Apart from this, particle problems are affecting not only in gas engines, also are creating technical problems in turbines (Knoef 2005).

Looking at the technologies, two groups can be distinguished in the BMG process. Firstly, the removal technologies with cyclones, barrier filters, electrostatic filters and wet scrubbers are exhibited in *Table B-1,* given in *Appendix B.*

As it is seen, particle removal methods are commonly used for small scale applications. These technologies are mainly applied in processes with low temperatures, where the particles appear more easily.

Secondly, the other tar removal technologies are basically used in gas combustion with engines and gas turbines. There are three general tar removal methods: Physical, thermal and catalytic. The main characteristics of these technologies can be seen in *Table B-2,* given in *Appendix B.*

Recently, Olga process has emerged as one of the most promising physical cleaning methods. This scrubber technology is characterised by removing physically and destructing tars before the producer gas leaves the gasifier. Thus, it is a promising technology for future pilot, “demo” and commercial plants. In addition, there are other impurities affecting the process and different methods to remove them, such as alkali metals, chlorine, sulphur, etc. Thus, entrepreneurs are aware of all these problems and a large number of R&D activities are carried out for obtaining the best results concerning cleaning methods.

4.2.4 Gas utilization

Producer gas obtained from gasification is used for the production of electricity, heat, fuels or other products from biomass. There are different types of final gas utilization systems depending on the mentioned applications.

Heat, Cement and lime kilns

In the case of heat applications, the produced gas is used into a boiler and most applications are focused on district heating, lime kilns, cement drying and other industrial processes (Knoef 2005). In the case of cement process, the product gas can be used not only for supplying energy but also as a raw material. Additionally, lime kilns are used for heating limestone and as in the case of cement, it has found an initial niche application. As a remarkable point, a lot of small scale Updraft gasifiers are implanted in several countries and it seems to be the most suitable technology for this application.

CHP – Gas engines

Concerning CHP, a breadth of knowledge is available and an important part of it are gas engines. These prime movers are suitable in a range of 100 to 2000 kW and its efficiency is around 30% (Hugue 2003). Often, in large scale applications, it is common the use of various gas engines working in parallel but the feasibility of this solution is limited. Concerning gas requirements, engines have higher tolerance to contaminants than turbines but it is known that tars cause serious problems to these prime movers (Knoef 2005). As it is seen in *Figure 4-2*, the status of gas engines is addressed between demonstration and ready for market phase. In general, the willingness to invest in gas engine based CHP-plants is limited due to the small expected market (Bolhar 2004).

CHP – IGCC

IGCC (Integrated gasifier combine cycle) is considered an important technology in large scale processes and due to the experiences from coal gasification, some components are reused and also, the scale up process is always faster. However, coal gasification has provided important experiences to other applications as well. Indeed, IGCC is suitable for fired and coal-fired systems. Currently, some plants have been successfully commissioned using this gas utilization, but their status can be located between demonstration and ready for market phase, as it is exhibited in *Figure 4-2.*

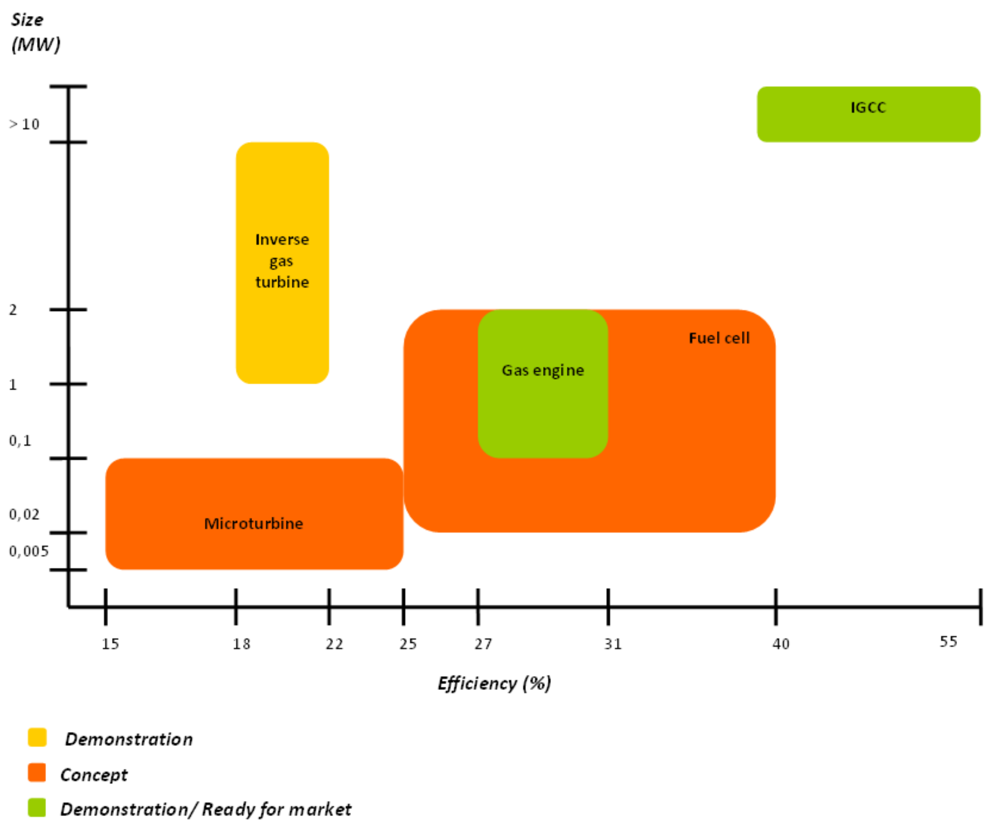


Figure 4-2. Size and efficiency of CHP technologies
Source: Hugue, 2003

According to *Figure 4-2*, the efficiency range of IGCC systems is between 40-55%. Additionally, with fluidized bed and entrained flow reactors, the IGCC can be possible to very large scale applications. The problem of this gas utilization system is that it needs to be pressurized and requires important gas cleaning specifications, reducing alkalis to prevent erosion (Iversen 2005). Additionally, CHP applications require turbines to be redesigned due to the lower pressures needed. As a result, the investment costs increase (Rodrigues 2003) and this may be taken into consideration by entrepreneurs.

Co-fire

Regarding coal fired applications, what happens is that the mixture between coal and biogas is burnt into a boiler. It is suitable to very large scale plants, as it is seen in the successful commercial concepts implemented. Due to higher temperature and pressure, the electrical efficiency is very high. The main problem is that, often, the system requires extensive cleaning methods mainly because when removing contaminants, higher steam temperature and pressure values are obtained. As a result, higher electrical efficiency is achieved (Palonen 2006).

Synthesis

Currently, syngas is mainly produced by fossil fuels but the alternative with biomass seems to be a promising concept for the future of renewable energies. This advanced application can be addressed as concept but extensive R&D activities are being carried out to introduce it in the market. Concerning applications of syngas, the production of ammonia as a fertilizer is the principle one. Then, hydrogen is used in oil refining processes and finally, the smallest part corresponds to DME or methanol production. Another important application is Fischer-Tropsch diesel production in which the producer gas requires high quality conditions. The F-T plants need very larges scales, >400 (Tijmensen 2002) in order to have the chance to compete against conventional refineries. Thus, syngas has an extensive range of applications but there are other important advantages. The potential of syngas is related to emission standards and it is essential for the future of biomass. By contrast, the raw gas lost during the process and the complex composition of the gas, make the evolution of this application difficult (Knoef 2005). Apart from that, the willingness of entrepreneurs to develop this technology is a reality nowadays but economical reasons always slow down its evolution.

Microturbines and fuel cells

Concerning important future BMG applications, fuel cells and microturbines are on the spotlight of promising technologies due to its potential energy production. Related with this, VTT, the technical Research Centre of Finland has predicted the future of power production technologies as it is shown in *Figure 4-3.*

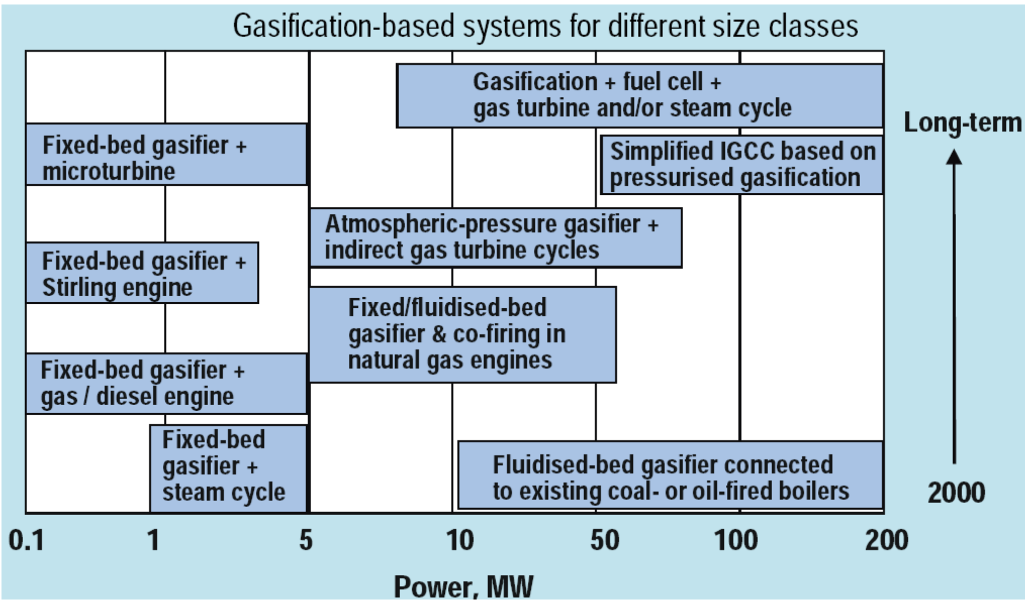


Figure 4-3. Gasification-based power systems for different size classes.
Source: Bioenergy: Cost reduction in the bioenergy system
http://www.iea.org/Textbase/work/2003/extool-excetp6/III-hely.pdf

As a starting point, fuel cell is an energy converter by a chemical reaction, using oxygen and hydrogen fuel. This technology can be an alternative to engines in vehicles and has the characteristic to generate heat and electricity. Currently, most investments in fuel cells come from the private sector and it is predicted an important market acceptation in the near future. The main discouraging factor is the high investment costs, but on the other hand, this technology allows an extensive range of efficiencies and it can be scale up to 2000 kW approximately, as it is seen in *Figure 4-2*. Moreover, the clean gas, obtained by fuel cells, allows some other niche applications, such as computer chips. Additionally, microturbine is the other promising technology and it consists on a small combustion turbine to small scale power generation and low efficiencies, as it is shown in *Figure 4-3*. Microturbines are fed by biogas but can also be used with hydrogen, propane, diesel or gas natural. Apart from their small size, they have important advantages, such as the low investment and operating costs, and the independence of the system. As it is known, these two technologies are under development but the willingness to develop them is enhancing all over the years (CERT 2003).

5 ANALYSIS OF FUNCTIONS

5.1 Countries landscape overview

In order to give some insights of the current situation regarding BMG technologies, an overview of the four selected countries is given in this section. The aim of this section is to understand how biomass gasification has changed during the past and assess the status of each technology and application. The following pictures show an evaluation of all pilot, demonstration and commercial plants in the related countries. This overview is based on different historical charts that can serve as an initial point for the two IS functions analysis: *Knowledge development and diffusion, and entrepreneurial experimentation*.

Sweden, Finland, Germany and Austria are considered important countries concerning BMG technology development. Additionally, the great effort in R&D activities has enhanced them as a reference in this area. It is known that only a few projects have achieved a commercial status, not only in these countries but also worldwide. However, current and expected future demands on emission reductions, the variety of applications and the variety of technologies give to BMG, a competitive advantage on the market. *Figure 5-1* shows the cumulative installed capacity in percentage. These two pie charts correspond to different periods, exhibiting how BMG technologies and applications have changed in the last years.

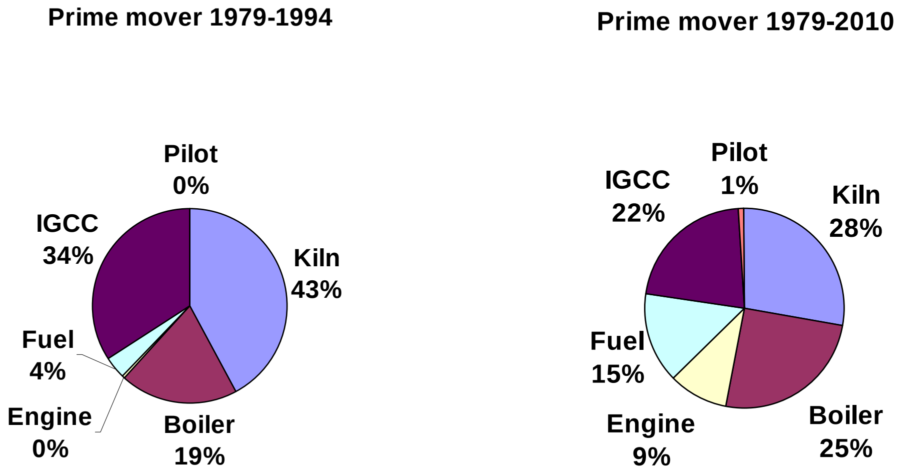
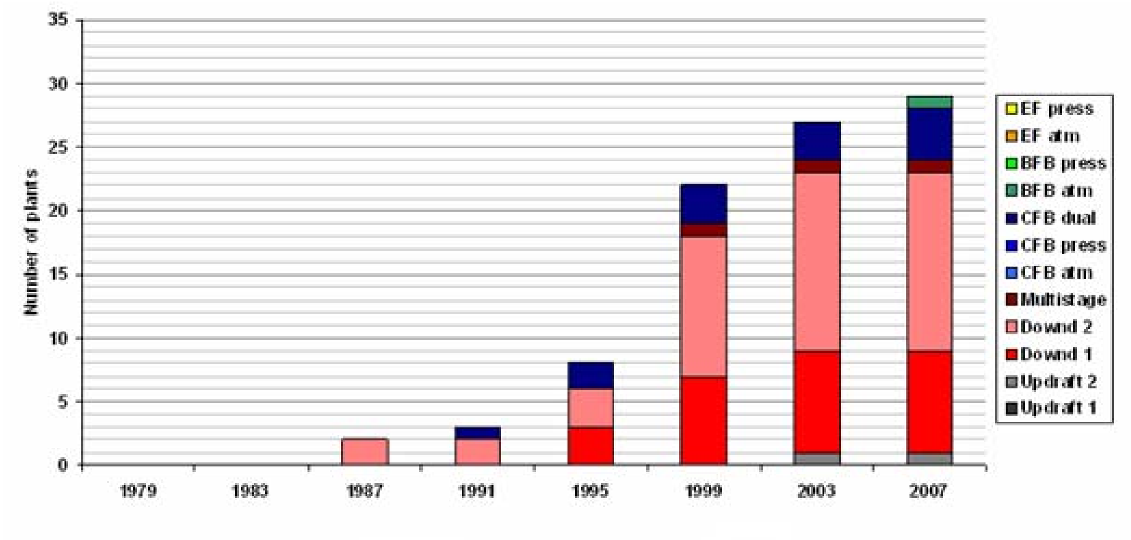


Figure 5-1. Comparison of percentage installed capacity for BMG applications

Since 1979 to 1994, heat production is considered the main application in BMG and several successful commercial plants were commissioned. As it is seen, 62% of the total considered plants in these four countries correspond to heating applications. During this period, some niche applications were established in the market, such as pulp and paper, cement and lime kilns. Moreover, several small to medium scale plants were focused on district heating applications. To clarify, the different percentage rate between these two heat applications is due to the large scale plants built to supply kilns. Apart from that, large scale CHP applications started arising with IGCC systems and only a few small scale plants were established for gas engines. 4% of the total installed size correspond to synthesis fuel.

Looking at the right chart, an important increase is observed in boilers. The main reason of that is the number of large scale plants built to supply co-firing boilers. Another remarkable fact is the massive development of gas engines for CHP, mainly for small scale plants. After that period, there was also an important increase in liquid fuels production for power and heat applications. Some of these fuels were used in IGCC systems.

Concerning CHP applications, a wide range of reactors have been comissioned in the past. IGCC and gas engines have been two important prime movers in this applications and they have been used with different types of reactors along the years. *Figure 5-2* shows their evolution, sorting the two different applications by scale and reactor type. Updraft 1 corresponds to the first generation of this reactor type and Updraft 2 relates to those that have suffered some modifications respect to its predecessors. The same classification has been applied for downdraft.



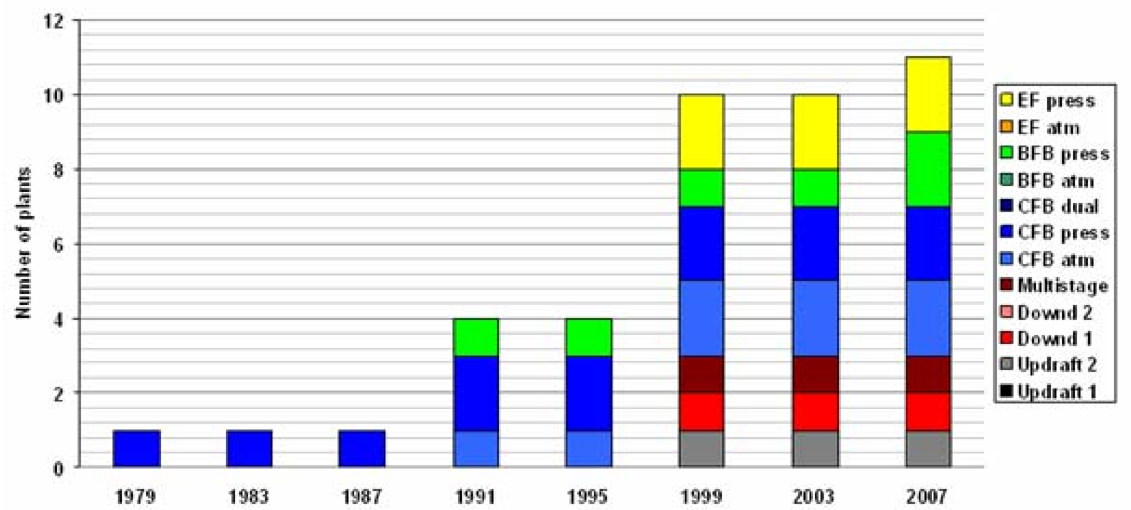


Figure 5-2. Number of installed gasifiers for power production sorted by reactor type.

As it is seen, the major evolution of BMG reactors started at the end of 1990's. Before that date, some fluidized gasifiers were coupled to IGCC systems and several fixed bed gasifiers to gas engines. Since 1990, a wide range of BMG reactors were applied for both prime movers but the main characteristic is the two different technology directions. On the one hand, an extensive variety of reactors were tested or used in IGCC systems, mainly based on fluidized gasification. In the case of gas engines, it is remarkable the great increase in the number of entrained flow gasifiers.

Following the gasifiers evolution, each of them has been used for a specific scale. *Figure 5-3* shows the gasifiers distribution considering scale and number of implementations. Moreover, these two different pie charts give an overview of the plants' features (number and scale) in the past.

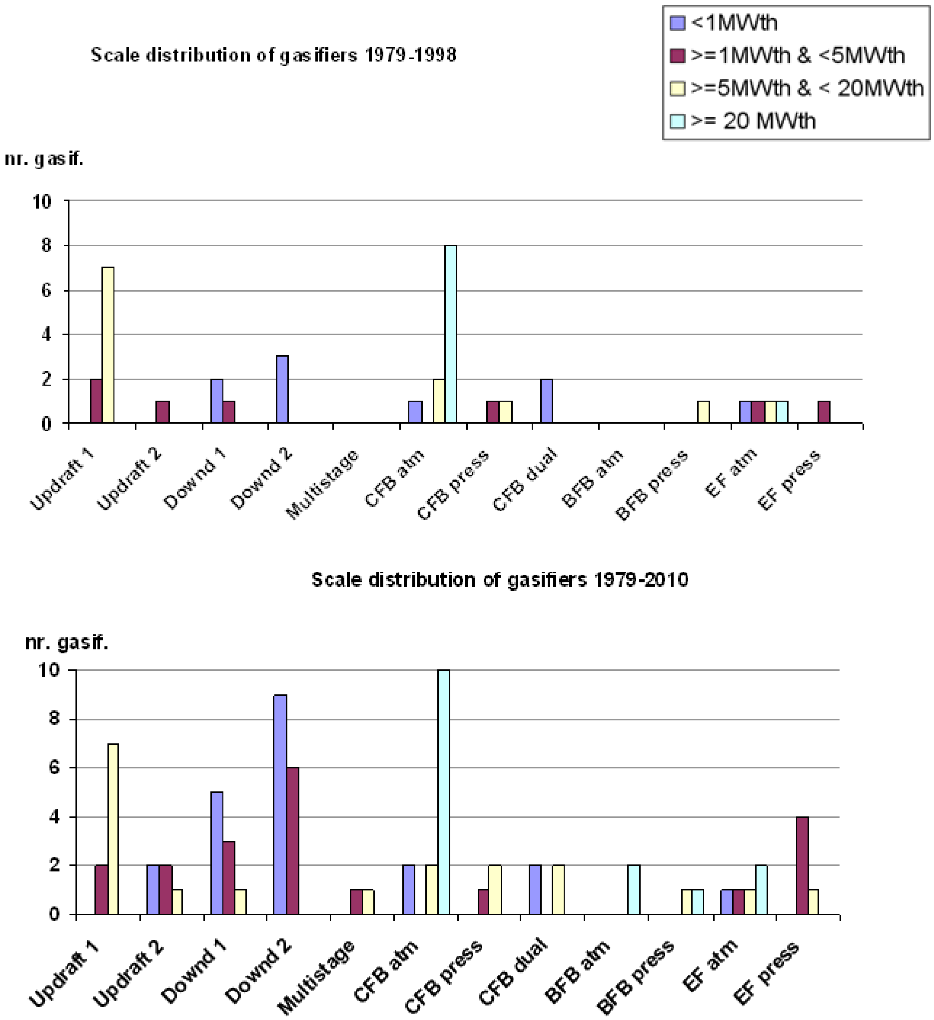


Figure 5-3. Power generation gasifier systems sorted by scale and reactor.

Looking at *Figure 5-3*, a great evolution has occurred in all types of gasifiers. Concerning fixed bed gasification, updraft reactors were initially used in a range between 4 and 6 MW_{th}, but the second generation of this gasifier was additionally used for applications under 1 MW_{th}. In the initial phases, downdraft gasifiers were scaled up to 5 MW_{th} and the same direction has been followed until nowadays. Finalizing with this group, multistage reactors are ranged between 1 to 20 MW_{th}, most of them being installed from 2000 on.

In the case of fluidised gasification, it is remarkable the large number of CFB gasifiers comissioned. This reactor is used not only in medium to large scale applications but also, and more commonly, in very large scale applications (> 20 MW_{th}). As it is seen, BFB has been applied on very large scale plants as well. Finally, entrained flow gasifiers have been used on a wide range of scales but the number of plants is limited.

To conclude, the wide variety of applications and technologies makes difficult the assessment of the two considered functions. Hence, this brief overview can be useful as an initial point for further studies; and it also helps to introduce the different technological trends in BMG. Nevertheless, an in-depth analysis of each country is needed for assessing *knowledge development and diffusion,* and *entrepreneurial experimentation*.

5.2 Sweden

5.2.1 Analyzing the entrepreneurial experimentation

Swedish *entrepreneurial experimentation* has been strongly influenced by changes in the energy policy along the history. Oil crisis in the 1970's and 1980's, the nuclear programme phase out and the deregulation of electricity market have conditioned the entrance of new entrepreneurs.

On the one hand, the governments have shown a willingness to ensure a reliable supply of electricity and other forms of energy based on renewable resources, specifically on biomass technologies, by the creation of R&D programmes. Moreover, the importance given by the government to biofuels in the transport sector is also contributing to create some expectations among the entrepreneur community. Currently, the government considers that there are enough further market opportunities for BMG to reach the commercial stage in the short-term. According to this institution, BMG should play and important role in the energy-intensive industrial sector, the transport sector, bio-fuel production sector and fuel based energy conversion sector. However, regarding the current experimentation status, it is clear that not all the possibilities have been explored, in part due to the lack of industrial infrastructure.

The existence STEM, the Swedish National Energy Agency, have also encouraged suppliers to keep experimenting even when the risk was important. The role of this institution has been providing national investment support for the development of global projects undertaken by associations of entrepreneurs. Another factor that strongly encourages the entrepreneurial activity, related with biomass technologies, is the great availability of woody biomass that reduces considerably the supply transport costs.

On the other hand, oil price variations has turned to be one of the main discouraging factors. During those periods in which the oil price has been high, there has emerged a positive competition among the different suppliers that have increased the entrepreneurial activity. Nevertheless, the willingness has decreased with the prices once the oil crises have passed. No further units of updraft or CFB gasifiers have been sold in Sweden due to low oil prices since 1986.

Entrepreneurial activity has passed through different stages since the first applications led by the Bioneer updraft gasifier. However, it is worth to emphasize that, in spite of the changes in the experimentation trends, there have been very few entrepreneurial actors that have taken part in the innovation process. It does not mean that they have not evolved but that the entrance of new actors has been affected by the lack of new market opportunities. This has also pushed some entrepreneurs to abandon their experimentation activities. Usually, when there is only one niche application a "funnel" effect takes place. All suppliers work in the same direction, in some cases developing the same concept simultaneously. Hence, it is important to stimulate the competence but always giving alternative market chances to those actors that have not succeed, in order to not waste experimentation resources. In this sense, it is interesting to mention the case of TPS. While they were competing against FW and Kvaerner for the lime kiln market, they did not success in selling their atmospheric CFB gasifier nevertheless, they did not give up and continued developing the concept. Later, they would be the chosen supplier for the ARBRE and BIG-GT projects. In addition, it is also significant the poor level of diversity in the number of entrepreneurial experimentation trends of each period. The following *Table 5-1* is a summary of the most remarkable experimentation trends undertaken by entrepreneur actors since the end of 1970's.

Table 5-1. Swedish BMG experimentation trends

Period	Entrepreneurs	Experimentation
1979-1979	Studsvik of Sweden	CFB IGCC for electricity production
1983-1998	Ahlstrom Pyroflow, Kvaerner, TPS	Atmospheric CFB for kilns and boilers
1985-1986	Bioneer, Eisenmann	Updraft gasifiers for District Heating through a boiler
1986-1990	Eisenmann	Updraft gasifiers for to replace oil in a lime kiln
1987-1996	Chemrec AB	Atmospheric EF Black liquor gasification for boilers
1991-/	ABB	Atm. CFB black liquor gasification for CHP
1992-/	TPS, ScanArc	Waste gasification
1993-/	TPS, FW, Vattenfall	Pressurized FB + hot gas cleaning for IGCC
1994-/	Chemrec AB	Pressurized EF black liquor gasification for IGCC

The first entrance of new actors, after the second oil crisis, was due to the creation of a niche market for atmospheric CFB gasifiers for heat applications, mainly kilns and dryers used in the pulp and paper industry. During this period Foster Wheeler, TPS and Kvaerner focused their experimentation activity on developing atmospheric CFB gasifier reactors. Different success levels where achieved by each one, since there were not enough market opportunities for all of them. Nonetheless, they all continued involved in gasification experimentation. The second entrance of new actors was during the development of black liquor gasification. This technology was created to turn a by-product (black liquor) from the pulping process (to produce paper) into a producer gas that could be used to increase the overall plant efficiency by either burning it in CHP applications or synthesizing biofuels. Chemrec AB was the only firm that sold a commercial version of the process based on an Entrained Flow reactor. Nonetheless, this application is still under development and will likely attract new entrants in the next years.

During the 1990´s, expected future higher power prices created a lot of expectations on the application of BMG for CHP. This led to the development of gasifier/gas turbine combined-cycle (BIG-CC), both at pilot plant and semi-commercial scale. Till now, high costs and lower electric prices have prevented the realization of some full-scale commercial plants for IGCC and it has caused the entrance of very few new actors. Only Vattenfall AB, a power generation company, decided to make a join effort with some Finish companies to develop a new IGCC concept for large scale applications. Nevertheless, the high investment costs and the low electricity prices prevented the scaling up of the concept by realizing demonstration plants. Due to the former, Vattenfall AB decided to withdraw from the project.

However, the still demonstration status of the technology concept and its potential are some indicators of a likely entrance of new actors once its feasibility has been proven. Another one is the big diversity in the experimentation trends.. This can be observed in the following *Table 5-2*.

Table 5-2. Diversity in Swedish gasification systems.

Application	Gasifier reactors used	Cleaning systems used	Gas utilisation systems used
Electricity & CHP	o Biomass Atm. CFB o Waste Atm. CFB o Biomass Press. CFB o Biomass Press. BFB o Black liquor Press. EF o Black liquor CFB o Waste Plasma decomposition reactor	o Hot gas filter + reformer catalyst o Gas cooler + hot gas filter o Three stages dry scrubber o Dolomite tar cracker + cold filter + web scrubber o Plasma gas cleaning for waste o Hot cyclone + scrubber o Water gas cooler + H2S absorbers	o Boiler + steam cycle o IGCC o Co-fired boiler + steam cycle o Dual Fuel Engine
Heat	o Atm. CFB o Updraft	o (low gas quality requirements)	o Kiln (FW, TPS, Kvaerner, Eisenmann) o Boiler (Bioneer) o Dryer (FW)
BioFuel	o Atm. EF BLG o Press. EF BLG o Biomass Press CFB	o Quenching reaction(inside the reactor) + Water gas cooler + H2S absorbers o Hot gas filter + Steam reformer	o DME Process development unit o MeOH Process development unit

Former suppliers of heating applications (Foster Wheeler and TPS) decided to take advantage of the chance by improving their gasifier reactors designs and by developing new concepts of gas cleaning systems to fit the gas quality requirements for CHP applications. On the one hand, Foster Wheeler, collaborating with Sydkraft AB commissioned, in 1993, the Värnamo demonstration plant (6 MWe/9 MWth), the world's first complete IGCC power plant using wood as fuel. On the other hand, TPS developed and demonstrated a hot gas cleaning process, based on a dolomite tar cracking catalyst, to use the gas in a dual-fuel engine for small scale electricity production. However, they did not succeed in selling the technology in Sweden and decided to continue the development for IGCC systems.

The lack of a standard gas cleaning method for the different power generation scales could explain new entrants distrust. There are some projects aiming to solve that problem. This is the case of "BMG Gas Engine Demonstration Project" developed by the Finish company Carbona Oy. One factor that should be also taken into consideration, when looking for niche markets for this type of applications, is the market possibilities offered by developing countries in Asia, where small scale biomass-based power generation technologies seem to be gaining importance.

Regarding the small scale CHP applications, there are still few activities and only few private people are engaged in small-scale demonstration activities. It is worrying the lack of networks that coordinates and supports this kind of experimentation as well as the difficulties to get information about the status of these systems.

Finally, waste gasification has also called the attention of some entrepreneurs, like ScanArc that has developed a plasma based technology for the gasification of new fuels. Moreover, some of the existing actors decided to experiment also in that direction. This is the case of TPS that modified their pressurized CFB concept, originally designed for biomass based CHP applications, to gasify waste. This application reached the commercial stage when the Italian company Ansaldo purchased the license to use it in their Grève in Chianti waste treatment plant. Other advanced applications like Bio-fuel synthesis have only been experimented at a laboratory scale or in pilot plants in some cases. The number of entrepreneurs working on that is low due to the uncertainty level. However, the technological advantages are well-proven. Other countries have reached a higher development in this fields and Sweden can not fall behind.

As it has been commented, the pulp and paper sector have offered manufacturers important chances. Having a look into a list of companies that owned plants with biomass gasifiers reactors installed *(Table 5-3)* it is easy to understand their importance when creating commercial opportunities.

Table 5-3. Swedish Plant owners and manufacturers.

Plant Owner	Sector	Manufacturer
Stora Enso (Sweden)	Pulp and paper	Chemrec AB
AssiDomän (Sweden)	Pulp and paper	Chemrec AB
Weyerhaeuser (USA)	Pulp and paper	Chemrec AB
Vilhelmina Värmeverk AB	District heating	Foster-Wheeler
Byggelit	Chipboard factory	Foster-Wheeler
Wisaforest Oy (Finland)	Pulp and paper	Foster-Wheeler
Norrsundet Burk AB (Sweden)	Pulp and paper	Foster-Wheeler
Karlsborgs Burk (Sweden)	Pulp and paper	Foster-Wheeler
Lahti Energia Oy (Finland)	Power generation	Foster-Wheeler
Portucell (Portugal)	Pulp and paper	Foster-Wheeler
Sodra cell Värö (Sweden)	Pulp and paper	Kvaerner Power
Ansaldo (Italia)	Waste treatment	TPS Termiska Processer AB

There are more than 15 medium and large scale pulping facilities installed around Sweden that are still using combustion based technology to obtain energy from the black liquor. This fact gives an idea of the importance of this sector when creating new market possibilities.

Another remarkable aspect of the entrepreneurial activity is the large number of changes in the organization charts of the Swedish entrepreneurial actors. The common trend is that small companies focused on R&D activities have been purchased by big groups, usually enrolled in either machinery manufacturing or large scale electricity production. Bioneer, Ahlstrom Pyropower (both acquired by Foster Wheeler), Sydkraft AB (purchased by E.ON Sverige) or Götaverken AB (acquired by Kvaerner Power) are some examples. Some more examples are shown below in *Figure 5-4*.

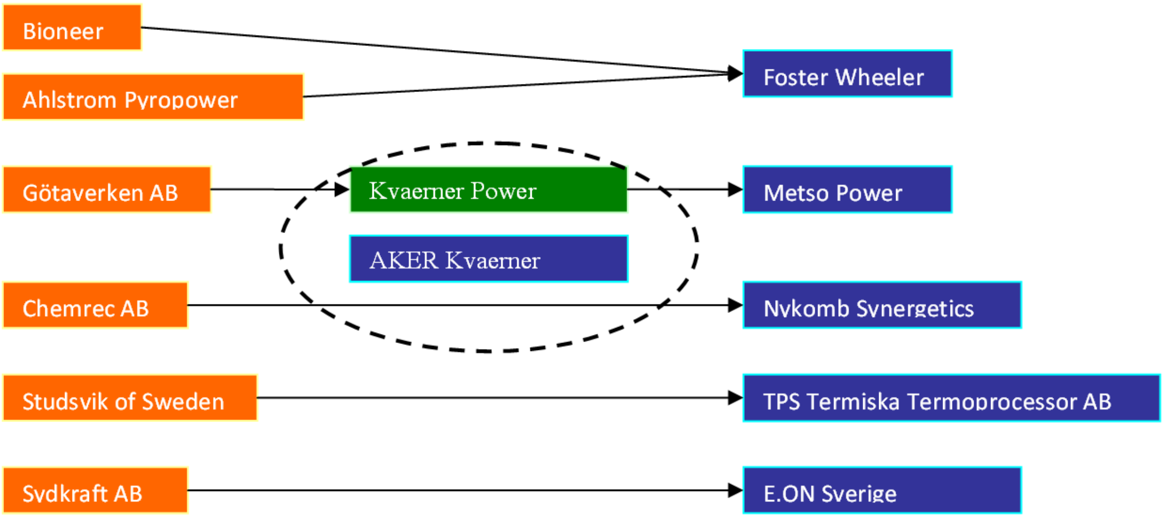


Figure 5-4. Changes in Swedish suppliers' organization charts

The great majority of the entrepreneurs taking part in experimentation are from Sweden itself. Nevertheless, the contribution of some foreign companies can not be omitted. Some countries like Austria (through Eisenmann), US (through Weyerhaeuser), Italy (through Ansaldo), Portugal (through Portucell) or Finland (through Bioneer) have increased the Swedish entrepreneurial activity by contracting Swedish manufacturers or by selling their technology to Swedish companies.

In conclusion, the entrepreneurial activity of Sweden if quite high compared with the rest of countries but the number of actors taking part is still rather low considering the future chances given by the technology. The considerable number of tangible projects shows that the technology has definitely overcome the initial stages of innovation. The first technical uncertainties have slowly disappeared thanks to the experience gained in demonstration projects with several accumulated operational hours. Despite the general belief that the potential of the technology is largely proven, there is still a widespread uncertainty about whether the market conditions will allow the technology to be considered as a serious alternative or not. In part this is because its commercial trajectory has been truncated various times by the changing oil prices nevertheless, it has been demonstrated that there is a small solid group of entrepreneurs that trust the potential of the technology, not only as a further opportunity but also as a current chance.

As a final remark, the government should make an effort encouraging small entrepreneurs to undertake experimentation on small-scale CHP applications as well as continue funding big entrepreneurs, and motivating plant owners to trust the technology.

5.2.2 Analyzing the knowledge development and diffusion

Biomass has always been considered a potential resource in Sweden. The big amount of wood available around the country guarantees the biomass fuel supply and makes the fuel transport much cheaper. Therefore, they have put a considerable effort on creating a solid knowledge base that allows biomass-based technologies to develop and BMG is not an exception. As their have acted as pioneers in the technology, most of the knowledge acquired and used comes from the national R&D associations and firms. Nonetheless, Swedish suppliers have taken advantage of this situation selling their technology and their systems around the world.

The importance of the Swedish pulping industries in the national industrial landscape has conditioned Swedish gasification knowledge base since the first biomass combustion boilers were installed in pulp and paper mills. The intense experience acquired from the several hours of operation of combustion reactors created a solid knowledge base to develop the first gasifier reactors to supply lime kilns. Since then, the learning process has occurred orderly and it can be divided in two main periods. On one hand, the first period, from 1970's to the early 1990's, was focused on heating applications. At its initial stages, learning by imitating became the main knowledge source. As it has been said, there was a previous knowledge base on biomass combustors due to the large number of paper and pulp mills working around Sweden, using burning biomass waste to obtain steam. This previous knowledge was used in the design of the first reactors. The scale up process of these fist reactors was quite fast, going from the testing stage to the commercial applications in a short period of time. In the case atmospheric CFB gasifiers for lime kilns, this process took less than three years, from the first developments by TPS till the first commercial installation in Pieteersaari. The confidence in the technology was so high that the demonstration stage was directly performed in the same commercial installations. In the case of small scale district heating the process take some more time, around six years.

After the first commercial installations a learning by using process started by accumulating thousand of operating hours. During this time, the main technical thresholds were related to the gas utilization system because they were not completely adapted to the new gasification systems. Some examples of those problems can be seen in *Table C-1*, given in *Appendix C*. In spite of that, the most of the problems were solved and the technology started to gain reputation among the actors. At that time, most of the large scale projects were undertaken by agreements between the supplier and the plant owner. Thus, the coordination was rather easy so there were not remarkable non-technological difficulties.

The low degree of gas quality requirements demanded by heating applications allows the suppliers to focus the research on the feeding system and the reactor. During this stage, updraft fixed bed was used for small scale applications and circulating fluidized bed working at atmospheric pressure was installed in large scale facilities. Some examples of successful plants were the three 4 to 5 MWth Bioneer updraft gasifiers installed in Vilhelmina Värmeverk AB and Byggelit (chipboard factory) or the 30 MWth atmospheric CFB gasifier installed in the Karlsborg pulping mill.

Once the electrical and CHP applications started to gain importance, suppliers started to design new systems putting more effort on the cleaning system efficiency due to the higher requirements on the gas quality demanded by gas turbines and engines. Thus, a new competence among existing companies began in order to create a new gas cleaning system standard. Moreover, other countries apart from Sweden intensified their research activity in this field increasing the competence among actors and accelerating the learning process despite of the great uncertainties about the viability of the technology.

The second period, focused on CHP applications and started during the 1990's. However, the transition between the two periods was not sudden at all, some research was carried out during the first period. For instance, TPS developed the MINO process an IGCC concept based on pressurized CFB in 1979. The concept could not overcome the conceptual phase at that time but, nevertheless, it started to set up a knowledge base that would become important for further developments. During this second period, the knowledge development was not as fast as the first one. In fact, it has not reached that commercial level yet and it is considered to be still in a demonstration stage. In some cases, it could be said that this slow and long performance have affected the expectancies of some entrepreneurs, creating uncertainty. The number of large scale demonstration projects in which Sweden has take part is considerable. Värnamo, WASTE, Brazilian BIG-GT or ARBRE are some examples. Not all of them have turned in success but they all have unfolded a learning process. Even failed projects, like Brazilian BIG-GT or ARBRE, have taught some interesting lessons to the actor community. One of these is that entrepreneurs should be concerned about a lack of organization or motivation before starting to think of how to solve the technological difficulties.

The technological thresholds encountered are mostly due to problems in the gas cleaning and cooling system as it can be seen in *Table C-2*, given in *Appendix C*. However there have also occurred some failures due to non-technologic reasons that have affected the reputation. This is still part of the learning process and, as long as further projects learn from this experience, it can become something positive at the end. The following *Table C-3*, given in *Appendix C,* is a compilation of some technological and non-technological difficulties of the studied projects

The knowledge creation process has turned out not to be linear at all. The demonstration plants not always are preceded by pilot plants of smaller scale and followed by commercial plants. There are several feedbacks and changes of the learning direction. One good example is the case of Värnamo demonstration plant. The facility was originally designed to demonstrate the viability of integrating biomass and combined cycles for the production of heat and power. The core of Värnamo plant was the Foster Wheeler's pressurized CFB gasifier. It is considered that this demonstration project was a great success due to the knowledge acquired through the large number of operating hours achieved, about 8500 hours of gasification runs and 3600 of operation as a fully integrated plant within 6 years (1993-1999). However, the plant never reached the commercial status, but it was used later by two different international partnerships to undertake other demonstration projects. These are the CHRISGAS project, aiming to manufacture hydrogen rich gas from biomass and the WASTE project, with the purpose of developing an IGCC concept fed with refuse derived fuels and other waste fuels. As it can be seen the success of a plant concept does not always lead to a scale up process, but sometimes it motivates more research activities trying to find new applications for the technology.

The following *Figure 5-5* shows the knowledge development process of Swedish technologies emphasizing the status reached by each one.

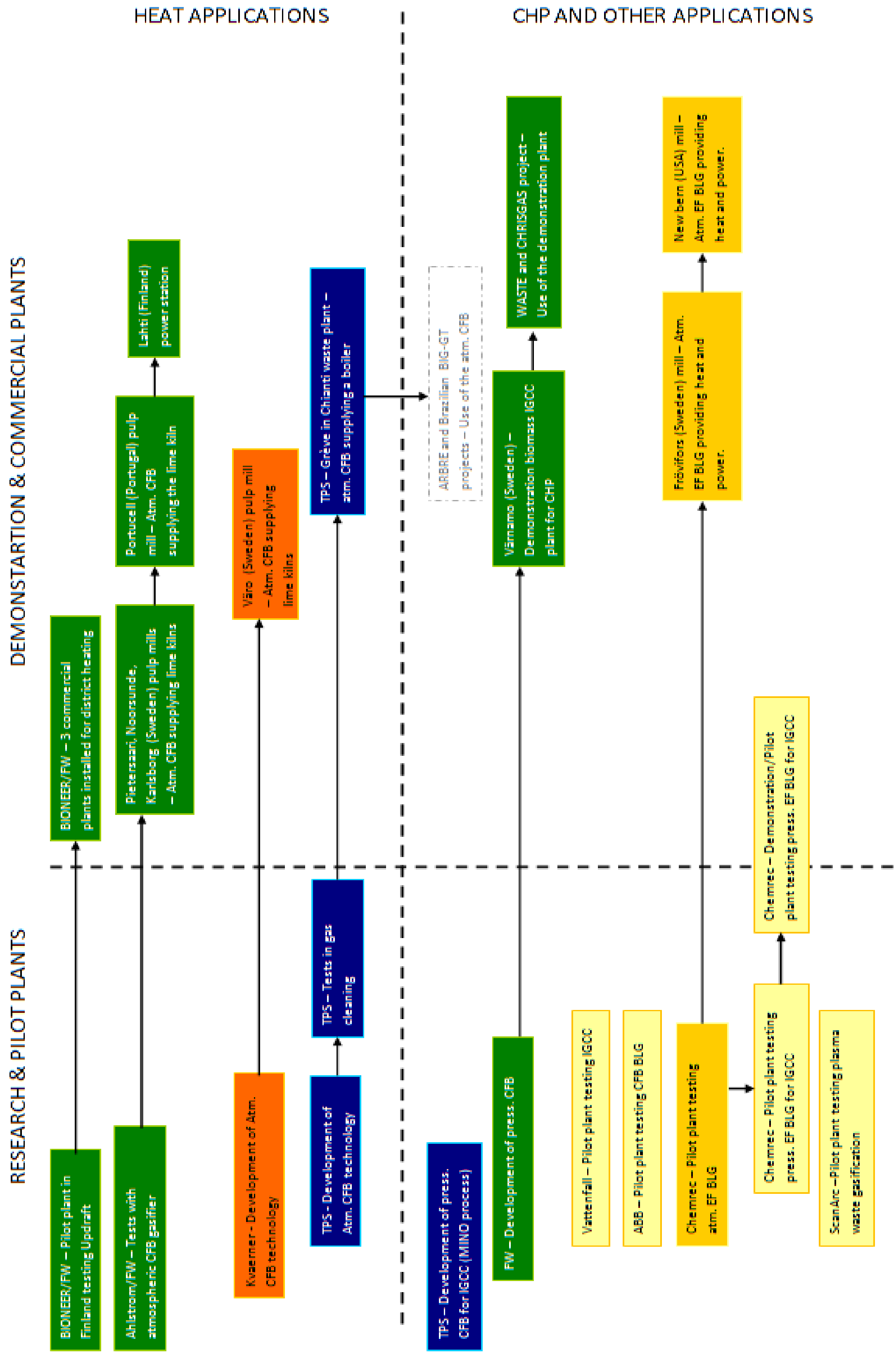


Figure 5-5. Evolution of BMG technologies developed in Sweden.

Concerning the intensity of research activities, the Swedish academic community has played a determinant role. Universities like KTH, Lund University, Luleå or Chalmers UT, as well as others, have developed both fundamental and process-oriented research working directly with suppliers. It is remarkable, for instance, the role played by KTH, putting in practise its long-time experience in thermochemical conversion of solid fuels by developing innovating gasification concepts. Some examples are the oxygen-blow pressurised gasifier, that would be later be used in the MINO process, or the chemical studies of fluidized bed gasification, that would be used later by TPS and Kvaerner in their atmospheric CFB gasifiers. The effort put on fundamental research and pilot testing by academic institutions has helped to overcome the first technological uncertainties, creating positive expectancies among the entrepreneurs. After the first technological uncertainties were overcome, more academic institutions started to engage in BMG research. Then, universities started to move on the development of conceptual systems as well as test the performance of determinate system components. Some examples are the High Temperature Air/Steam gasification by KTH, the specially designed High Temperature Entrained Phase reactor by Lund University, the small scale F-T concept for local use by Mitthögskolan or the small cyclone gasifier (combination of gasifier and solid separator) by Luleå TU.

The main advantage of the knowledge generated by this kind of research is that is much more accessible for the rest of the actors than the private-owned research. However the strength point of the latter is that the results of the research have been put into practice more easily since it has been much more process oriented. One example of these private-owned research associations is TPS, one of the most successful Swedish suppliers, which has also developed various research projects. In the following *Figure 5-6* the most important R&D associations are listed jointly with the most important demonstration and commercial plants.

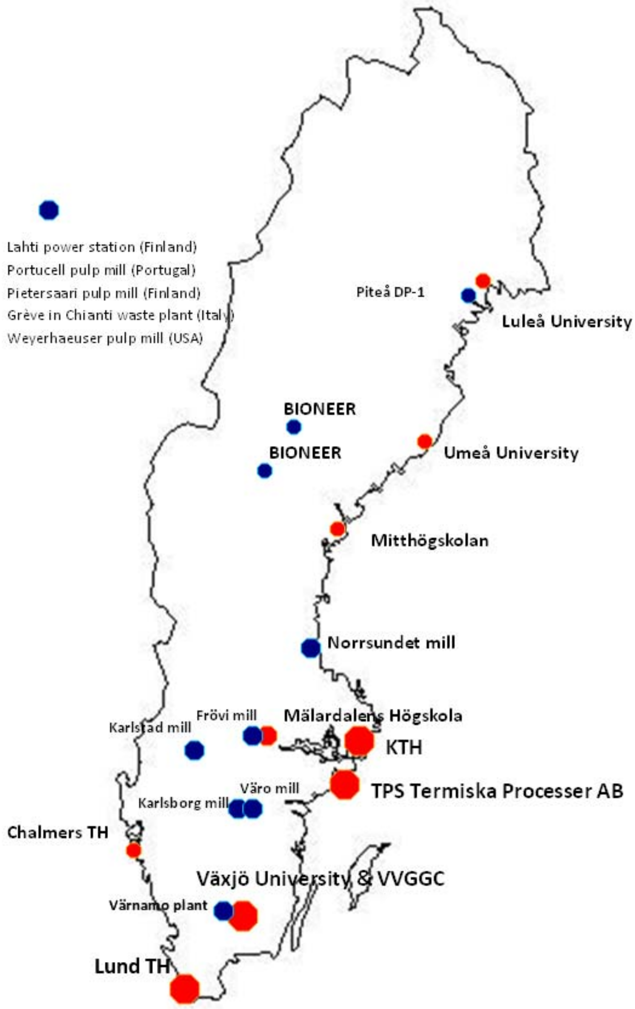


Figure 5-6. Location of Swedish BMG research activities.

The knowledge acquired through these research activities has not always turned in larger demonstration projects or commercial applications. In some point, connections between universities and manufacturers should be strengthened, for instance by starting up new collaboration projects. However, there have been some cases where manufacturers have used some part of the knowledge developed in academics institutions. Kvaerner and TPS, for example, used the research developed by KTH in order to develop an atmospheric CFB gasifier concept to compete against FW for the pulping mills market. Despite this last example, manufacturers often prefer to rely on their own know-how instead of shared of imported know-how leading to an inefficient use of the current knowledge stock. It has even been the case when the research work performed by universities has been repeated by the companies as well.

In 2003, an evaluation of the energy R&D programmes showed that the quality of the work performed was in most cases good, but that measurable deployment of results in society or by industry was low. This was claimed to be the result of the long time existing gap between obtaining the results of R&D activities and its implementation.

A part from the research individually developed by the R&D associations, usually with pilot small pilot plants, big research projects, aiming to build large scale demonstration plants, are gaining more and more importance lately. These types of projects are usually undertaken by various different actors that conduct research in a specific field. A project coordinator will be responsible for putting the results of the research all together. The major advantage of this kind of projects is that several entrepreneurial connections are created, being one of the main sources of knowledge diffusion. Some information about the most important projects is given in *Table C-4*.

Most of these projects are carried out in order to demonstrate the viability of a promising concept, facing the great amount of uncertainties and risks. Sharing these with other actors and countries, companies are more willing to spend resources and money on research. As it can be seen, thanks to this global projects, connections between Sweden and more than ten countries have been created, including Germany, Austria, Finland, UK or France. Moreover, the quantity of funding received from EC research programmes such as sixth framework programme or Alterner II is greater. In addition, the Swedish National Energy Administration, STEM, is funding some national projects. The main drawback of these projects is that they require a lot of coordination between suppliers and great willingness from funding associations. When, for any reason, this is not possible, the likelihood to fail raises dramatically. Two examples of projects that failed, due to mainly organizational reasons, were the ARBRE project and the Brazilian BIG-GT project.

Finally, it is necessary to stress that there is a certain amount of knowledge acquired during the WWII that have been seldom used. Small downdraft gasifiers coupled to gas engines were developed in the universities using previous WWII knowledge but currently there are only few activities. There is an important knowledge base but there is not support from entrepreneurial activities to develop it. The diffusion of this knowledge is also quite poor. Actors should make more efforts to create conditions that could enhance the development of these applications since its potential have already been proven by some demonstration projects developed in other countries.

In conclusion, it could be said that, considering the knowledge base created in Sweden, the *Knowledge development and diffusion* has progressed quite well. It has been a progressive process that has always evolved keeping an eye on the current application requirements without forgetting the research on potential future applications. However, there have been very few plants built for the demonstration of BMG for fuel production and advanced CHP applications. Without incentives for the construction of facilities that give the opportunity to demonstrate the commercial feasibility of this technology, it will be impossible to gather the operating experience needed to make the technology competitive. Additionally, it has been observed that the interest from the different actors have shifted from medium scale heating applications to large scale combined fuel and power production. Small scale applications, with very few actors working on it, have been focused mostly on power production. Nonetheless, there has not been a great interest in its development.

5.3 Finland

5.3.1 Analyzing the entrepreneurial experimentation

Some entrepreneurial activities have been carried out during the history of Finland, collaborating different actors and resulting in an important number of technologies and applications. However, this technology is changing rapidly and new solutions, alternatives and possibilities are arising over the time. Thus, successful tangible implementations of R&D projects can reduce the uncertainty in the entrance of new actors. *Table 5-4* is a good starting point to know the experimentation trends in Finland.

Table 5-4. Finish BMG experimentation trends.

Period	Entrepreneurs	Experimentation
1981-1983	Ahlstrom	CFB pyroflow combustion technology, lime kilns
1980's	Bioneer VTT	Updraft gasifier for district heating applications
1991-/	Tampella (75% Enviropower) VTT	Pressurized BFB gasifier IGCC applications
1998-2006	VTT Foster Wheeler	CFB gasifier boiler co-fired
1998	Ekogastek Oy	Updraft gasifier for CHP applications
1999-2002	Condens Oy VTT	Novel gasifier: feedstock density and catalyst development
2001-2001	VTT	BFB gasifier: Aluminium recovery and boiler

As it shown in *Table 5-4*, entrepreneurial experimentation has undergone important changes over the years but the initial concepts were focused on heat applications. The main reason of that was occurred in the 1980's, when the Finnish government supported economically the technology development of this application. Since this period until the late 1990's, two potential actors entered in this sector: VTT and Bioneer. On the one hand, VTT was created as a research centre under the domain of the Finnish Ministry of Trade and Industry. On the other hand, Bioneer was a manufacturer of paper. Both of them were focused on heat applications, with an Updraft gasifier for district heating and a Circulating Fluidised Bed reactor for lime kilns. The famous "Bioneer" Gasifier has been a point of reference in Updraft gasification and it was initiated with extensive tests in a variety of feed stocks. In the case of A. Ahlstrom Corporation, it developed a pilot CFB gasifier for proving a pyroflow combustion system. Hence, the willingness from the own government and these two potential actors has strongly influenced in successive entrepreneurs. As a result, three gasifiers of pyroflow combustion were implemented, two in Sweden and one in Portugal. Moreover, Bioneer commissioned nine commercial plants, three in Sweden and six in Finland, being the main reference of updraft gasification. In addition, some other entrepreneurs took advantage of the potential of BMG, providing their own plants, as it is shown in *Table 5-5*.

Table 5-5. Finish plant owners and manufacturers.

Plant Owner	Sector	Manufacturer
Wisa Forest	Pulp and paper	Ahlstrom
Kauhajoen Lämpöhuolto Oy	District heating	Bioneer
Oulun Seudun Lämpö Oy	District heating	Bioneer
Jalasjärven Lämpö Oy	District heating	Bioneer
Kiteen Lämpo Oy	District heating	Bioneer
Parkanon Lämpö Oy	District heating	Bioneer
Ilomantsin Lämpö Oy	District heating	Bioneer
Lahden Lampovoima Oy	Fossil fuel fired	Foster Wheeler
Kokemäenjoen Lämpö Oy	District heating	Condens Oy, VTT and Carbona Oy
Corenso United Oy Ltd	Core board mill	Foster Wheeler

Looking at the table, the development of the Updraft gasifier by Bioneer was essentially important for the addition of plant owners. The importance of district heating applications is a reality in Finland, with around 50% of its total heating production.

Another remarkable fact emerged in the late 1980's, when the energy consumption critically increased in the industrial sector and Finland focused its R&D projects on higher production of CHP. As a result, some entrepreneurial projects based on IGCC applications, appeared soon. Enviropower Inc., 75% owned by Tampella Power (Finland) and 25% by Vattenfall AB (Sweden), started some tests with a pressurised BFB gasifier and a hot gas cleaning system in 1991. Therefore, this joint venture between two different countries not only allows obtaining more interesting points of view, but also makes easier developing BMG systems. Different examples of ownership changes in organizations are exhibited in *Figure 5-7*.

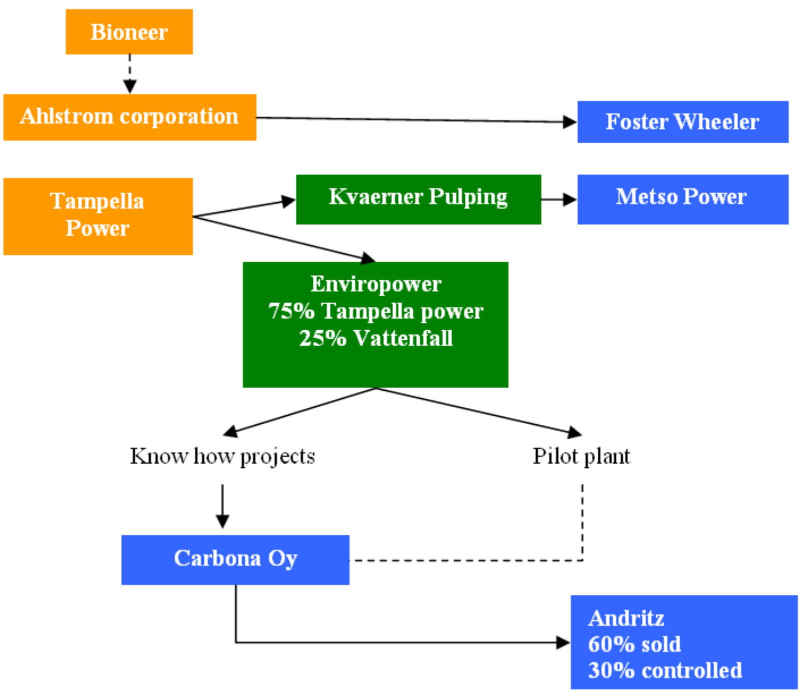


Figure 5-7. Changes in Finish suppliers' organizational charts

As it is seen, 60% of Carbona Oy has been sold to Andrizt but only a 30% of the company is under control. This negotiation started in 2006 but there is an intention to buy the rest in an early future. Another important organizational change occurred when A. Ahlstrom Corporation bought the Bioneer Company and then, Foster Wheeler acquired Ahlstrom, *Figure 5-4*.

The entrance of Tampella was occurred because it was working as a heavy industrial machinery manufacturer, supplying pulp and paper facilities. Then, Tampella's interest for BMG emerged. As it is seen, this joint venture evidences the effort of Finland in creating CHP applications. By contrast, non gasification plants of this type were built during the 1990's due to the influence of some negative factors, as the lack of electricity market regulation in the Northern Europe and the non sufficient economical support from the government. Therefore, the change of interests, due to the necessities, affects considerably, not only the evolution of BMG but also the addition of more actors, arising big uncertainties.

After that, in 2001, two important facts produced a high impact to BMG in Finland. Firstly, the pilot plant established in Varkaus by VTT and in 2005, the "BIGPOWER" project for large scale applications. These two projects enabled the entrance of international entrepreneurs, bringing new perspectives into the sector. Consequently, some commercial plants were successfully commissioned by Finish actors, most significantly the Varkaus plant in 2001 by VTT and the Skive project in 2008 by Carbona Oy (Denmark). Therefore, the importance of CHP applications showed the interest in this technology, not only in Finland but also internationally. In addition, the successful results from the commissioned plants gave to actors a point of reference for starting new BMG projects. As an example, *Table 5-6* shows the breadth of technologies in each application during the history of Finland and it can be useful for decision makers.

Table 5-6. Diversity in Finish gasification systems.

Application	Gasifier reactors used	Cleaning systems used	Gas utilisation systems used
District heating	• Updraft • CFB	-	• Boiler • Firing lime kilns
CHP	• Novel-Updraft/downdraft • Downdraft	• Tar reformer + Gas filter + Scrubber • multicyclone scrubber	Boiler - engine (two gas lines)
	BFB	Cyclone + particulate removal	IGCC
		Tar cracker + gas filter + scrubber	Boiler + IGCC
	CFB	Gas filter + Reformer catalyst	Boiler co-fired + IGCC

It is worth to highlight the diversity and possibilities in each application. In the case of heating in the 1980's, two important reactors were developed and this experience encouraged the entrance of new actors, even though they focused their further R&D projects in other applications. Relating CHP, some intensive efforts were done through VTT, developing BMG technologies. The technology possibilities were quite extensive and it is demonstrated in 1990's, when the alternative of Finnish electricity production was the co-fired boiler. Due to this interest, several entrepreneurs carried out different R&D projects investigating this technology concept, such as "GASASH", "UCG project" or "EU/ Lathi STREAMS". The results of them were two successful plants in Lathi and Ruien, as it is exhibited in *Figure 5-8.* Concerning the main actors involved, VTT was the coordinator of all these projects, improving and optimising the gasification process of the plant. It is well considered the ability of this company to manage important projects in BMG and it reduces the uncertainty of entrance. Thus, a leader in this sector ensure the strength of these kind of projects. Apart from that, some other companies, such as Foster Wheeler, collaborated in some of these mentioned projects. This US based firm bought by Ahlstrom, was steam boilers supplier during the WWII. An interesting observation is that several companies firstly worked in something related with the application of BMG and then, entered in this sector as entrepreneurs.

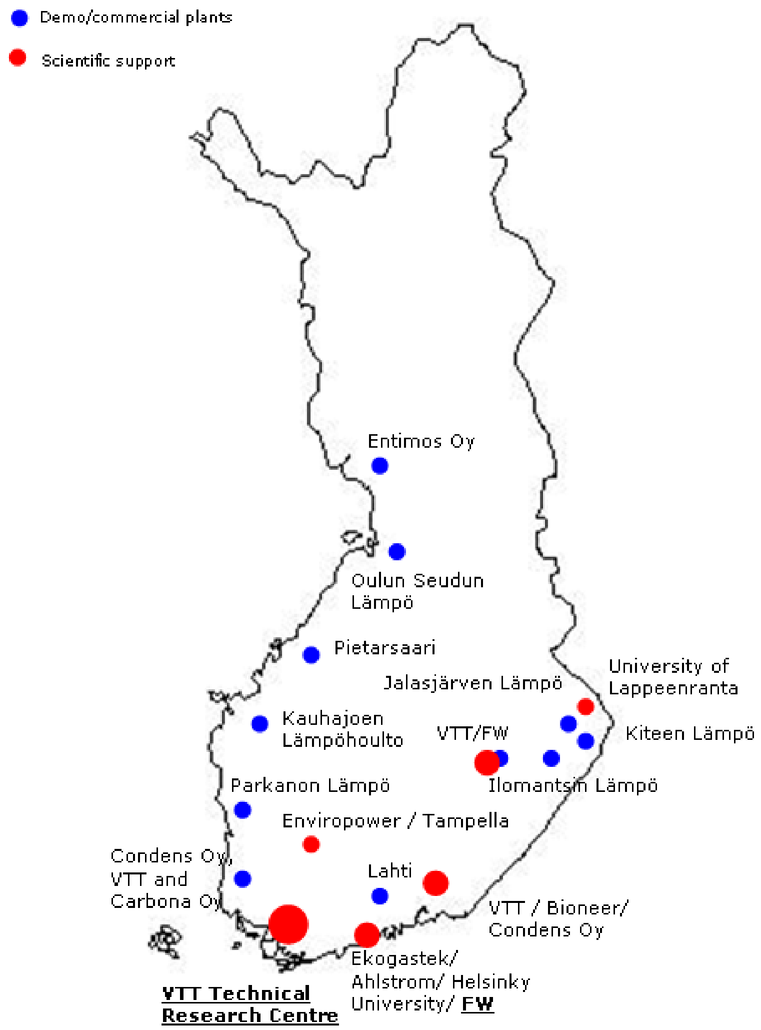


Figure 5-8. Location of Finish BMG research activities.

As it is seen, the nearly location of Foster Wheeler and VTT have enhanced their own cooperation and other public and private entrepreneurs have taken advantage of this circumstance, participating in the same projects. Another important aspect that encourage entrepreneurial experimentation is the international cooperation. A close relationship between foreign firms seems to be important and it is seen with Denmark, Germany, Austria and specially, Sweden.

To conclude, the efforts' intensity, the economical contributions from EU and other associations and the coordination from VTT, allowed the participation of international and national entrepreneurs, making easier the addition of new entrants. However, the individual "leadership" of VTT can generate doubts about the efficiency of the system and the addition of more actors taking decisions could be important to improve it, as the example of the Austrian network "ReNet". Another negative aspect is the lack of integration in international projects. VTT is creating their own R&D projects and it is not participating in foreign ones, so the international collaboration could be essential for other Finish entrepreneurs to open doors abroad.

5.3.2 Analyzing the knowledge development and diffusion

Biomass is considered an important renewable resource in Finland, with a 20% of the total consumption of primary energy and mainly coming from wood fuels. The Finnish government is working on enhancing the opportunities in BMG, mostly in CHP applications. The reason of that dependence is the large population and the possibilities in the industry (VTT 2002). Additionally, it is known that since the commission of the nine Bioneer plants (Kwant 2004), the main strategic partner is Sweden. It seems to be an important support for Finland because this alliance is maintained until nowadays. But apart from that, the contribution of the European Commission and TEKES enhance the economical possibilities for developing BMG.

Research activities related to BMG have been extensively developed in the country, not taking into consideration the decrease of interest during the 90's due to non technical factors, such as the bad market regulation or non sufficient support from the government. Until the end of the 1990's, most R&D projects were focused on fuel feeding, testing a variety of feedstock for the production of BMG (VTT 2002). These research activities were mainly oriented on biomass/waste fuel gasification, being essential for further developments of next gasifiers and applications. A R&D project that can be highlighted is the Updraft gasifier tested by Bioneer and VTT, generating twofold consequences. On the one hand, this project produced a failure due to the high bulk density and it was taken over by Condens Oy, together with VTT, solving the problem with a forced fuel flow process. On the other hand, the characteristics of the "Bioneer" gasifier were promising and the "Novel" gasifier maintained these features in the development mentioned above. Following with learning experiences, the chlorine content in fluidized gasification produced risks of corrosion in some parts of the process. Then so, two projects were carried out for removing chlorine emissions and new knowledge was put into practice, using plastic waste, gas cleaning and co-firing. Thus, some projects produce failures that emerged new solutions and some others learn through the past experiences. This experience seems to be an important factor for enhancing the learning process and, in Finland, is demonstrated that most of the projects have been influenced by cumulative knowledge. Therefore, the innovation process is continuously regenerating new ideas and most of them are the consequence of "*learning-by-doing*" and "*learning by failing"* actions.

During the 1990's, the Finnish interest was focused on CHP production for large scale applications. This knowledge was considered technically ready to implementations due to the successful results in the feeding system with a range of fuels. Then, after the 1990's, the R&D projects were oriented on cleaning systems improvements and it is currently under development. As it seen in *Figure 5-9,* the initial activities were focused on hot gas cleaning processes and ash removal systems. Then, the following research activities became more specialized, with the addition of ultra cleaning systems and process optimization. Recently, looking at VTT further developments, the direction seems to be oriented in a similar way: Waste gasification, process optimization and hydrogen technologies.

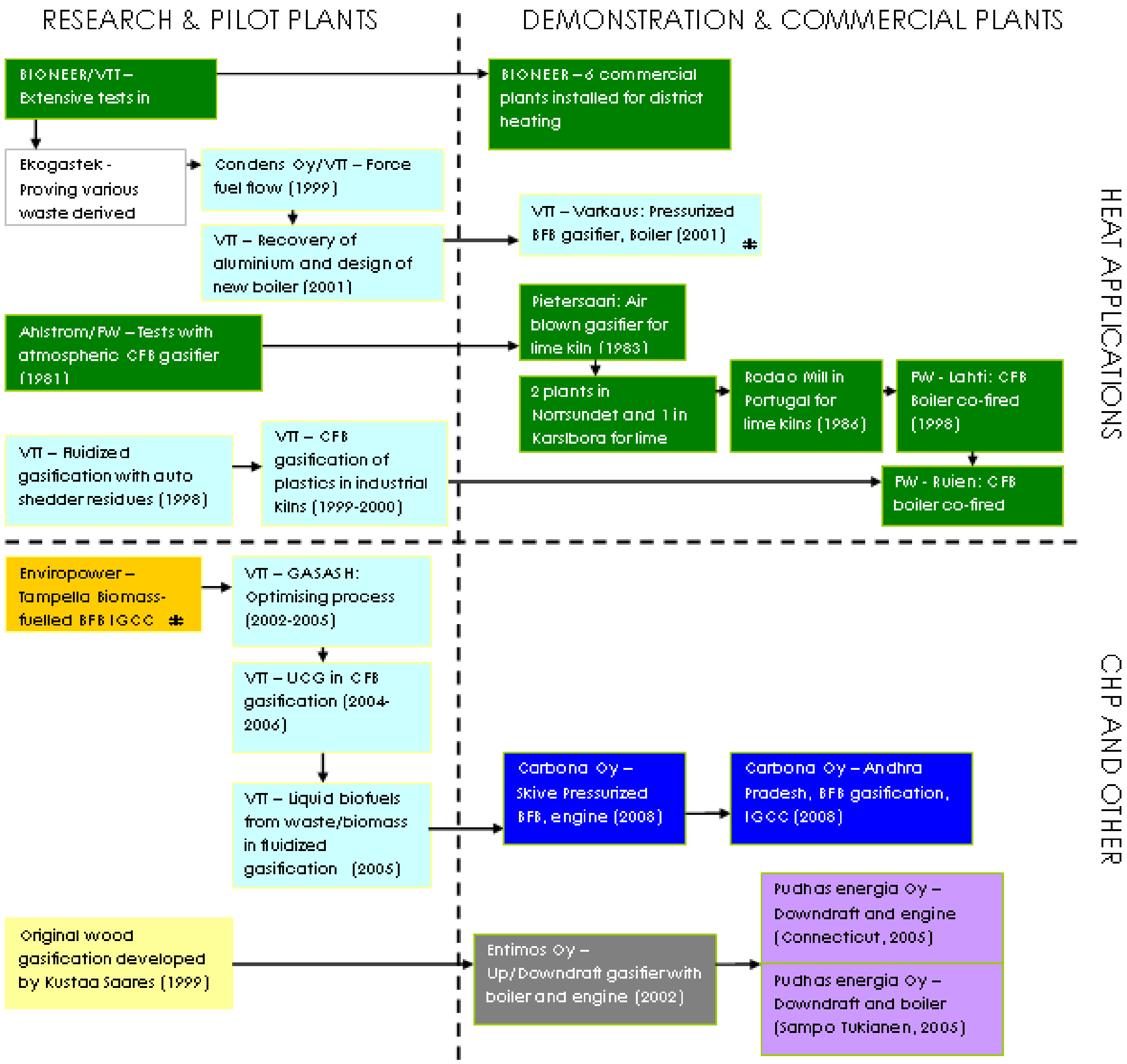


Figure 5-9. Evolution of BMG technologies developed in Finland.

Regarding the nature of the knowledge, most researches come from the public sector leaded by VTT Technical Research Centre. Often, the public and private knowledge is well combined under the domain of VTT. Concerning the public sector, several universities have collaborated in these projects, sharing scientific know how. This is the case of the Technical University of Vienna and Helsinki that helped in the BIGpower project, creating the fundamental and technical basis of developments. Moreover, the technical research centers, apart of VTT, play an important role in the public base knowledge and some are integrated in important projects. A remarkable example of international partners in that respect is the Energy Research Center of Netherlands and the "Asociación para la investigación y cooperación industrial de Andalucía" (Spain) in the GASASH project. By contrast, most private actors are involved in the technological basis of the development, contributing with their own experience in the sector. This is the case of GTI Chicago that collaborates in the Enviropower project with an important contribution to the IGCC system. As kari Salo (Carbona Oy CEO) said:

"*GTI has a long experience on fossil gasification and just recently started with biomass gasification*". Other important private actor is Foster Wheeler, due to the extensive integration in BMG projects. Its technological contributions have been translated in successful results for enhancing the learning process. Therefore, these two types of knowledge are considered well combined.

Looking at the global projects in *Table C-5* ,given in *Appendix C,* the imported scientific and technological knowledge seems to be quite efficient. The great work of VTT Technical Research Center, working as the coordinator, allows sharing the know how among countries. It is important to point out the NoE BIOENERGY[4] project, within the collaboration of eight leading institutes in the bioenergy field. This project created a successful bioenergy chain to produce heat, electricity and fuels. Therefore, this project exemplifies how Finland deals with knowledge and the successful results implicated on it.

Last developments can be characterised as internationals due to the number of countries involved. Additionally, the R&D activities were, since the beginning of the millennium, basically focused on cleaning systems and optimisation, but the most important project was the BIG Power project referred to three promising gasifiers. Thus, the breadth of technology development seems to be clear and also the diversity of knowledge from different countries has been an important feature in the last activities.

To conclude, the successful coordination of VTT, the well combined public and private knowledge, the continuity of the research activities and the international perspective in the Finnish projects, seem to be the main characteristics of Finland. Moreover, the intensive efforts for developing CHP applications and the successful results in heating production through "learning by doing" are enhancing greatly knowledge development and diffusion.

5.4 Germany

5.4.1 Analyzing the entrepreneurial experimentation

Entrepreneurial activity has been intense in Germany due to various factors that have created good conditions for long-term investments encouraging entrepreneurial actors. At first, the government established a supportive legal basis characterized by guaranteed feeding into the grid, long-term fixed prices for every kilowatt per hour electrical power produced from renewable energy sources to be paid for by the consumers. In addition, the definition of "allowed" biomass and new legislation on biofuel (tax-free), among other factors, has also boosted the renewable energies. However, there have been some factors that have slowed down the growth of the entrepreneur experimentation. One of the principal factors is the difficulty of innovative small and medium enterprises to get access to finances because of the ever growing resistance of banks to deliver credits. This has affected the number of

[4] http://www.bioenergy-noe.com/docs/au0007_bio_poster_v04.pdf

small and medium scale projects undertaken. Other factors have been the economical advantage of combustion technologies using negatively priced fuels or ups and downs of the everyday politics that introduce changes in the subsidy programs, thus causing critical situations for the enterprises which depend on the highly fluctuating market demand.

In 2002 there was a shift of political and financial attention in gasification from combined heat and power generation to the production of synthesis gas for biofuels. Consequently, the number of large plants built had been higher than the decentralized plants. This opened the door for giant strategic projects with the aim to increase the energy density of biomass in numerous distributed CHP biomass plants and the construction of central gasification and biofuel production units. However, it is necessary to say that it also hindered the previously achieved progress in the technological development of small and medium scale (Kwant, 2004).

Despite the number of research activities carried out, German entrepreneurial experimentation has suffered the lack of coordination of a system full of actors experimenting in a great variety of technology applications. The entrance of new entrepreneurs has been rather low for a long time. The last effort made by the actors community aiming to reach a global agreement on the developed applications has been quite successful and German actors have decided to invest all their resources in developing new advanced applications. However there is still a big diversity in the experimentation, with suppliers trying to demonstrate the performance and feasibility of new systems. Some of the most important current trends are given below in *Table 5-7*.

Table 5-7. Diversity in German gasification systems.

Applic.	Gasifier reactors used	Gas utilisation systems used
Heat	• Straw moving bed gasifier • Atmospheric CFB (Lurgi)	• Combustion chamber • Cement kiln (Lurgi) • Co-firing with coal • Co-firing with residues
CHP	• Multistage (DM2, AHT, BEV, Oxytec Energy, …) • Modified downdraft "Juch" (EC Espenhain, PPS) • Waste pressurized EF (NOELL, FUTURE ENERGY) • Moving bed BGL with solid waste (Lurgi) • Pressurized EF (Future Energy, Choren) • Atm. CFB (UMSICHT)	• IGCC (DM2, Future Energy, PPS, SVZ) • Gas engine (AHT, UMSICHT, EC Espenhain, CHORen, Oxytec), • Gas turbine (Pipeline systems)
BioFuels	• Moving bed BGL with solid waste (Lurgi, SVZ) • EF (Future energy, Choren) • Super critical water gasification (FZK)	• Methanol (SVZ, Choren, Karlsruhe) • F-T (Choren)

As it is shown in *Table 5-7*, there are various actors developing concepts oriented in the same application but with important differences among them. This lack of standardization is one of the remarkable characteristics of the German BMG landscape. Historically there have been three big entrepreneurs that have pushed the use of the technology to commercial stages: Future Energy, Choren and Lurgi (look at *Figure 5-10*). On the one hand, Future Energy and Choren have chosen to adopt EF for gasification of biomass and waste. While Choren has developed the Carbo-V process for liquid fuels production, Future Energy has developed the GSP-type entrained flow gasifier for feeding any type of pulverized or pumpable fluid biomass feed. Both technologies have shown a successful demonstration stage. Carbo-V is near the commercialization stage and GSP had already been in operation since 1988 at Schwarze Pumpe processing solid waste streams.

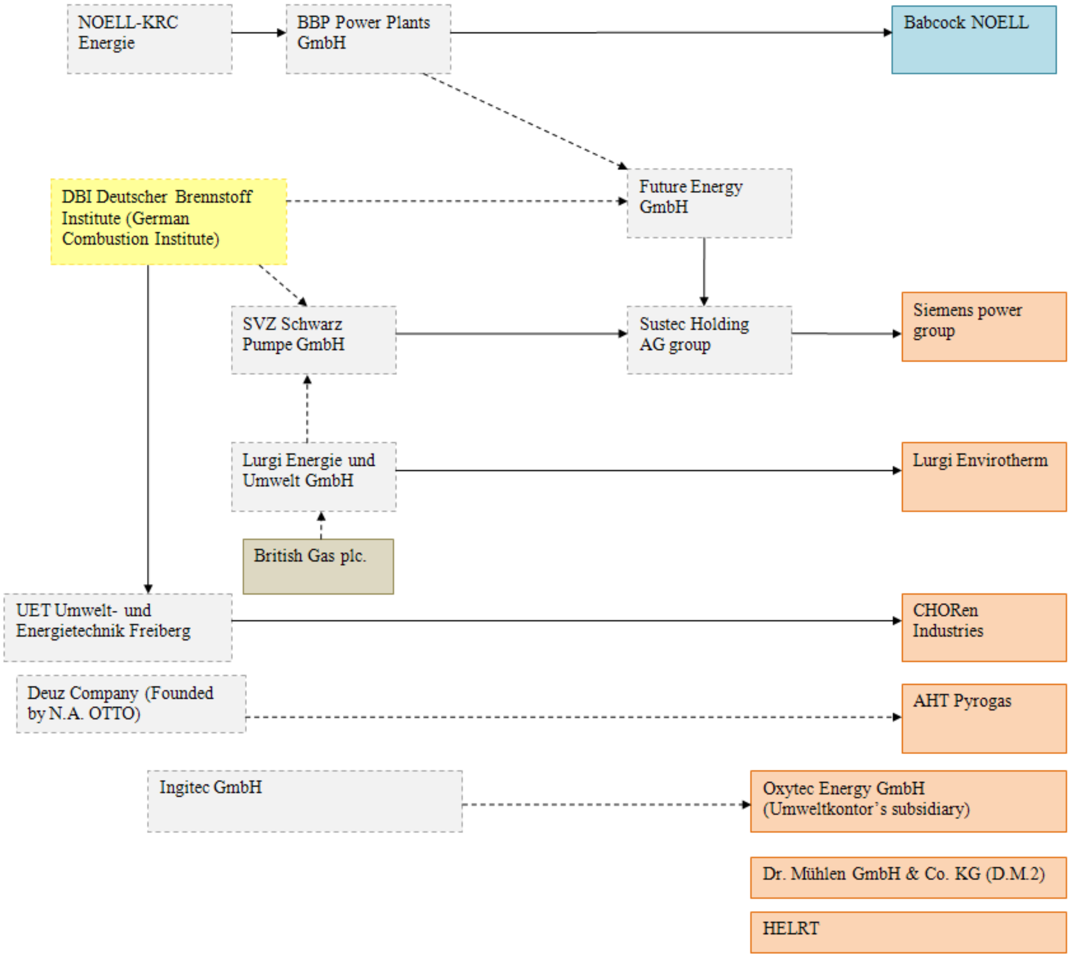


Figure 5-10. Changes in German suppliers' organizational charts

On the other hand, Lurgi has developed two gasification concepts. Jointly with British Gas, they developed the so-called BGL (British Gas Lurgi) gasifier, which consisted in a stationary bed slagging gasifier primarily used for the generation of highly energetic syngas, mainly required for the methanol synthesis. Moreover, they developed a CFB-gasification concept, mainly used in the waste-to-energy power generation sector as well as cement fabrication. The first commercial plant of this type was commissioned in Pöls (Austria) for firing lime calciners. Two more large scale plants for supplying a cement kiln firing and coal co-firing were commissioned. Nevertheless, due to an inadequate market pull among other reasons, Lurgi stopped its biomass gasification market efforts and sold both technologies to Envirotherm[5] GmbH. The technology development trends of the most active entrepreneurs are shown below in *Figure 5-11.*

[5] http://envirotherm.de/content/e39/e137/e48/index_eng.html

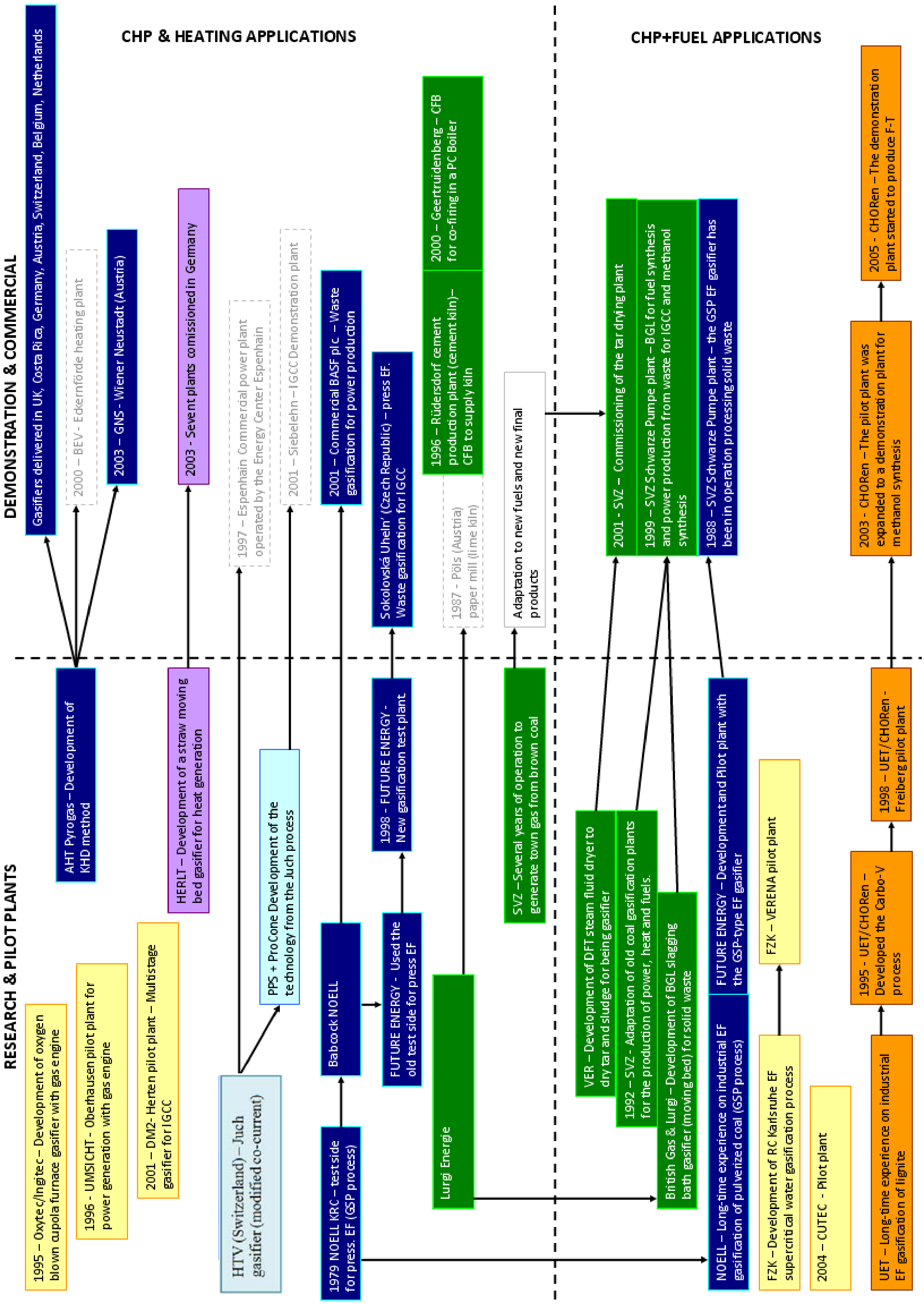


Figure 5-11. Evolution of BMG technologies developed in Germany.

It is important to highlight the fact that these three entrepreneurs have common roots, which go back to the East German DBI, Deutscher Brennstoff Institute (German Combustion Institute). Additionally, before entering the BMG business, these three actors were enrolled in the development of coal gasification processes gathering a long-time industrial experience.

Working in a smaller scale, there has also been two important entrepreneurs that have succeed in developing a commercial technology and selling them. These are AHT Pyrogas and HERLT. Both have sold its gasifiers in German and other countries. AHT Pyrogas developed a double zone gasifier based on the KHD technology using the gas in a co-generation module. HERLT developed a moving bed gasifier for heat generation fed with straw. Seven plants have been commissioned around Germany since 2003.

There are also some private own research associations that are developing promising concepts that might in the future be commercialized. Some of these are the multistage gasifier developed by DM2 Verwertungstechnology with a 1MWth pilot plant in Herten, the air-blown atmospheric CFB by UMSICHT with a 500kWth pilot plant in Oberhausen or the Oxygen Melt Gasification concept developed by OxyTec Energy. All these are designed aiming to be used jointly with IGCC and gas engines for power applications. Moreover, with regard to gas synthesis usage CUTEC has engineered an atmospheric CFB gasifier and the research center of Karlsruhe is developing a BtL process jointly with Future Energy.

Due to the change of direction in the knowledge development, more focused on biofuel production, German entrepreneurial experimentation is still growing and new entrepreneurs are to enter. The potential of the German industry and its commitment towards the use of new biofuels, gives BMG a lot of chances compared with the rest of the countries. In the near future it is expected that the production of synthetic gas and fuel and the gasification of straw might be demonstrated with at least technically positive results. It is believed that a scale-down of the biofuel production plants in order to fulfill the demands of smaller industries and a scale-up of the power production plants would attract more entrepreneurs. In fact, along the history there have been European suppliers that decided to try in the German market, and some of them succeed in selling the technology. This fact suggests that the there is still a lack of coordination between suppliers and demand.

Despite the diversity in the offered technologies, there has not been found yet a clear profitable industrial process which allows the integration of the gasification technology. Even when the demonstration stage has been overcome successfully, the experimentation and consequently the improvement of the technology will be interrupted due to the absence of entrepreneurs willing to make use of the technology. This has been one of the factors that have made difficult the entrance of new actors in Germany. When the demonstration stage is enhanced for a long time, even if the feasibility of the technology is well-proven, the technology development runs the risk to fall into a death point. If there are not available markets able to integrate the technology in any stage of the process those entrepreneurs that decided to experiment will interrupt their activity and in some cases they would even quit the business. One example of that was Lurgi, a part of the financial difficulties and technical thresholds, the absence of a niche market for their large scale heating applications pushed the company to halt the BMG marketing efforts.

5.4.2 Analyzing the knowledge development and diffusion

Germany has a long-time experience in coal conversion applications from the production of town gas. This previous knowledge base has been used as a solid starting point for research projects. However, despite the intensive research activity, there is a lack of coordination when setting the knowledge development direction. This is one of the reasons why formulating a technology development strategy for advanced biomass conversion have become one of the main goals in energy policy.

Currently, one the main targets of the established renewal energy policy is developing BMG for CHP and for producing organic base chemicals and fuels. Waste gasification has also had a great importance. In fact, the worldwide largest renewable waste gasification plant has been built and operated at Schawarze Pumpe. The operation of this plant has allowed various further developments in gasification processes as well as synthesis gas conversion processes.

Despite most of the German BMG knowledge base has been developed inside the country itself, it does not mean that it has not imported knowledge from abroad. A good example is the Pyrogas KHD technology or the Juch-type co-current gasifier developed by HTV. Both technologies are imported from Switzerland and have reached the demonstration or commercial stage.

As it has been commented above, the knowledge development has been characterized by a lack of order and organization. It has been stated in some of the articles published by EEV, Society for the Promotion of Renewable Energies, (FEE.e.V. 2001) that it has been a discontinuous process with the majority of projects suffering from technological immaturity and insufficient investment. There have been some positive factors, like the large number of actors that have demonstrated a certain interest in the technology or the previous accumulated knowledge in coal gasification, that have not been properly boosted. The lack of coordination among actors involved in research of an emerging technology such as BMG led, sometimes, to the repetition of failures without making use of the previous acquired knowledge. This has slowed down the technology development and in some cases it has interrupted it. Regarding the long scientific tradition and rich industrial experience in coal gasification accumulated in East-Germany until the beginning of the nineties (where lignite was gasified to obtain town gas and syngas for gasoline production), this has only been used by a reduced group of entrepreneurs and mainly in large scale applications.

Another of the reasons of this discontinuous process could be that the first commercial applications of the technology, with low gas quality requirements, never reached the commercial stage and could not gather the experience needed to set up a solid knowledge base for further developments. Firstly, heating applications of the technology, did not get enough reputation and there didn't emerged clear niche markets that let the technology develop through a learning by doing process, except for Lurgi and HERLT which commissioned some plants. Lurgi commissioned three different commercial plants, two supplying kilns and the last one supplying a co-firing boiler. However the first one, in Pöls (Austria) failed due to some technical problems related with the gas cleaning system and then there was a gap of nine years till the commission of the second plant in the Rüdersdorf cement plant.

On the other hand, HERLT developed a moving bed gasifier fed with straw for medium and small scale applications that resulted to be quite successful. In fact, the company is still selling that technology[6]. First combined heat and power applications, based on steam cycles, did not reach a solid commercial scale either. The situation was quite similar to the first heating applications with one large scale supplier, Noell, and another medium and small scale supplier, AHT Pyrogas. Despite the high degree of uncertainty, it is important to point out that neither of those entrepreneurial initiatives failed at all as it is proved by the various commercial units sold. That could mean that if the government had motivated more entrepreneurs to trust the possibilities offered by the technology the reputation of the technology might have grown significantly. Anyway, that was not done and a good opportunity to gather experience for future advanced applications was wasted. Furthermore, another factor that interrupted the knowledge development was the failure of some important projects due to non-technical difficulties sometimes combined with technical obstacles. Espennhain, and Siebelehn are examples of failed projects due to difficulties related to suppliers financial capacity or feedstock price. In addition, there were important projects that failed basically because of technical complication like the overestimate system electrical capacity or efficiency and in, some cases, because of the inefficiency of the cleaning system. These failed projects are just another proof of the immaturity of the technology caused by the lack of operational experience. A list of some failed projects and its cause is given below in *Table C-6* and *Table C-7.*

A part from these, there were other smaller failed projects affected by non-technical difficulties like fusions and fissions among companies; unrealistic estimation of costs and time to the aim as well as lack of staff with gasification modern expertise; management deficiencies, especially over-concentration on immature technology without profitable main business; suspicion of investment fraud; short-sighted tactical considerations of operational costs and expected profit rates, presumably too low; too high natural fuel costs and too low prices for heat and power to allow profitable operation or low or nil capital resources of innovative small and medium enterprises (FEE.e.V 2001).

[6] http://www.herlt.eu/impressum.html

Then, after those first failures in the development of the technology and thanks in part to the first IEA meeting in 2001, the energy policy and the BMG technology research trends of the country shifted completely to the development of advanced applications. The previous knowledge base was quite weak so there was an important investment by the government in research. Following this, various development, test and demonstration projects were initiated. The interest in generation of methanol and synthetic gas rose significantly. In addition, some demonstration projects with integrated combined cycles started.

It seems that this change in the development trends became an inflection point for the German BMG. Currently, seven years after, German's primary interest is still in developing BMG for CHP and for producing organic base chemicals and fuels. CHP plants are usually small scale units, many of these in early stages of commercialization, and the production of synthesis gas is developed in larger plants, often combined with waste gasification processes.

With regard to research and development activities, Germany is one of the countries with the largest number of R&D associations working in BMG. Moreover, it looks like the cooperation among researchers and suppliers have got an important improvement. On one hand, institutes are concentrated on developing new gas cleaning systems and fluidized bed and entrained flow reactors as well as testing fuel cells and microturbines with producer gases of different quality. In addition they are trying to obtain hydrogen rich gases suitable for being turned into fuels and chemicals or being burned in IGCC systems. On the other hand, important technology suppliers like SVZ and CHORen show a great commitment towards fuel production, building and scaling up their pilot and demonstration plants and combining them with CHP applications. Additionally the collaboration between gasifier suppliers and gas engines suppliers like G.A.S Energietechnik, MAN Dezentrale Energiesysteme (both from Germany) or GE Jenbacher (Austria) is strengthening the intensity of research activity concerning CHP applications.

This improvement in the cooperation and this change in the development targets have placed Germany again on the top of the European countries in terms of BMG. The knowledge base formed is strong enough and, now, the most urgent need is the existence of entrepreneurs willing to use it. Furthermore, the government should make more efforts to concentrate technological development in a unique biomass gasification center in order to improve the diffusion among the different German regions. The following *Figure 5-12* shows the situation of the associations working with BMG gasification.

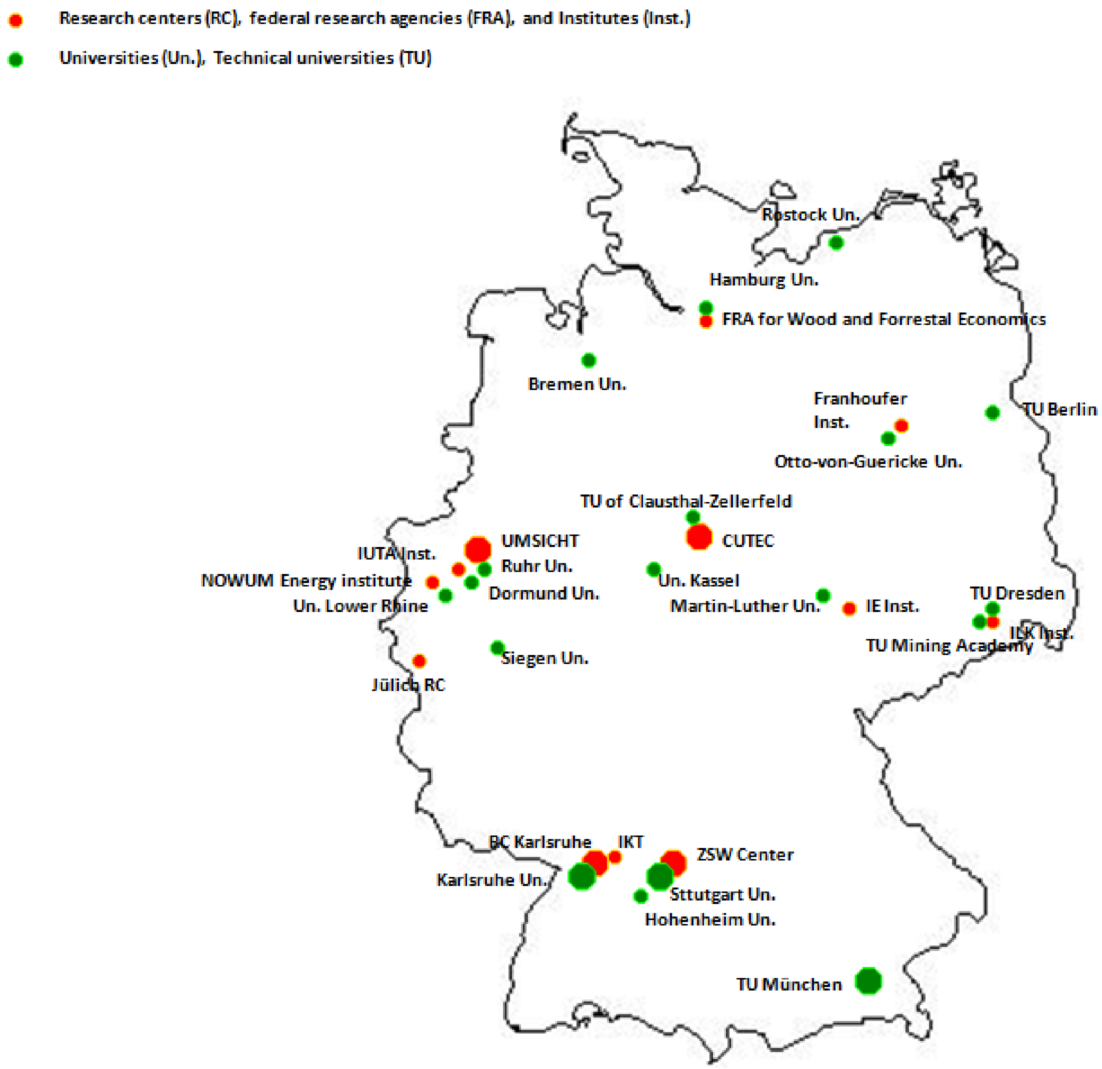


Figure 5-12. Location of German BMG research activities.

As it can be seen, almost all the country regions are carrying out some kind of research initiatives. It is worth to highlight the role of UMSICHT (Fraunhofer Institute for Environmental, Safety and Energy technology), CUTEC (Clausthal Environmental Institute) and ZSW (Research Center of Karlsruhe) as the main research centers and Technical University of Munich and the University of Stuttgart as the universities with the highest degree of activity related to the research in BMG.

Research activities concerning advanced biomass applications are gaining more attention. *Figure 5-13* shows the number of associations among a sample of 30 that are developing specific research related to different kind of aspects. Biofuels and hydrogen production from synthesis gas as well as fuel cells are being developed in six different associations. At the same time, microturbine-based power concepts are also being studied by four different institutes. As a consequence, gas cleaning has also become a matter of concern among the researchers within thirteen associations developing different gas cleaning concepts. Tar analysis and its transformation have also been widely studied by eight different research actors.

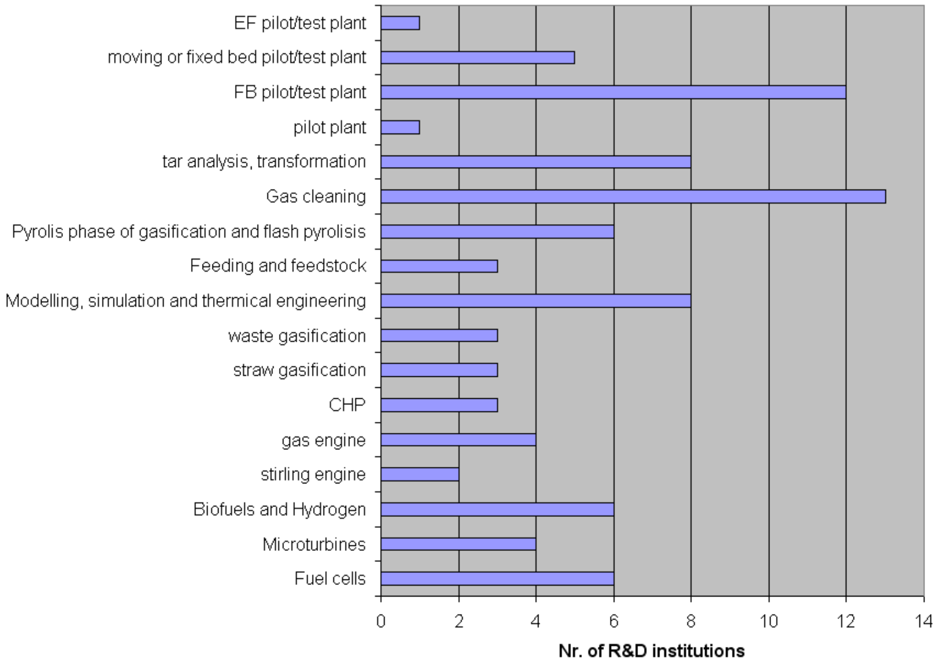


Figure 5-13. Research orientation in German R&D institutions

Additionally, one of the features of the Germany research that really enhance the knowledge base is the impressive number of pilot plants built. Looking at *Figure 5-13* it is possible to count more than twenty five pilot or test facilities installed. Most of them based on fluidized bed gasification, both CFB and BFB.

In November 2001, the first meeting of IEA Thermal Gasification of Biomass Task in Germany was organized (FEE.e.V 2001). The aim of the conference was drawing a picture on the current state-of-the-art of the technology. One of the conclusions of the meeting was that, despite all the progress, there was an urgent need of R&D, considering that the intensity of the German Research was lacking behind in comparison to the USA and the avantguarde in Europe, that was Austria, Finland and Sweden. Moreover, there was not an efficient guidance since the responsibility for the coordination of the research was split between three different federal ministries and the authorities of every fifteen states. The international co-operation was also rather weak at that time.

Seven years later, the situation has improved considerably. The willingness of the actors taking part in research and the amount of the participants has grown up. There is still a lack of coordination among the different actors, although some of them, mainly ZSW and the University of Stuttgart, have acted as leaders pushing the rest. These institutes have also played a very important role in the knowledge diffusion taking part in various European projects and sometimes coordinating them. In the following *Table C-8*, given in *Appendix C*, some of the principal projects, funded by the European commission in which German institutions have participated are listed.

European Commission funded research projects are the most powerful diffusion tool, both within the country actors and the different European countries. The table shows that Germany has been involved basically in two types of projects: the production of hydrogen rich synthesis gas for advanced applications and the development of small scale gasifier models for low-cost decentralized power production. German actors have coordinated various important projects like RENEW or AERGAS. ZSW has taken part in four European projects, all of them coordinated by German actors, and it is currently coordinating AERGAS II with the aim to develop a low-cost gasification process, based on a fluidized bed reactor with integrated in-situ gas cleaning, for the conversion of biomass into a product gas with high hydrogen concentration. On the other hand, the University of Stuttgart has taken part in six different projects, acting as coordinator in the ISCC project. The main target was to develop a gasification process with integrated in situ CO2 capture. This capturing process initiates a shift reaction in the product gas composition increasing the concentration of Hydrogen up to 95% in some cases.

It is also important to highlight that since Germany signed the biomass agreement of IEA after the first meeting in 2001, international cooperation has grown. Austria has become the most important partner collaborating with Germany in six projects. At the same time connections with Scandinavian countries have also being enhanced, especially with Sweden, with whom Germany has carried out four different projects together.

5.5 Austria

5.5.1 Analyzing the entrepreneurial experimentation

The use of biomass as a source of energy in Austria amounts to approximately 11 % of the entire primary energy demand and it is increasing over the years. After the energy crisis in the 1970’s, the public funding was focused on district heating applications and in the 1980’s, the Austrian Chamber of Agriculture started researches in wood and bark gasification. Then so, the first implementations immediately appeared for lime kilns but the incentive structure “feed-in-tariffs” pushed electricity production from Biomass (combustion) and made gasification projects possible. Thus, BMG started emerging in Austria and consequently, some actors initiated entrepreneurial projects for developing this technology for CHP applications. Then, different alternatives started arising, such as the boiler co-fired concept, but the lack of subsidies reduced the possibilities in this branch and entrepreneurs decided to be involved in more profitable and also necessary technologies. As it is shown in *Table 5-8*, most experiments have been focused on energy production.

Table 5-8. Austrian BMG experimentation trends

Period	**Austrian Entrepreneurs**	**Experimentation**
1993-1999	TU Vienna, AE Energietechnik, Babcock, Jenbacher Werke	FiCFB + engine
1997-2001	TU Graz, Austria Energy & Environ	CFB gasifier, boiler co-fired + engine
2002-2004	TU Vienna	Hydrogen rich gas from biomass and remove tars
2004-	TU Graz	Staged gasification- Fixed bed gasifier and IC engine
2004-2007	TU Graz	Gas cleaning tech. and Fuel cell materials (SOFC)
2004-2007	TU Vienna, Repotec, Kraftwerk Güssing	Syngas for future combustion engines
2005-2006	TU Vienna	Minimum ecology standards: Policy and efficiency
2005-2008	TU Vienna, Repotec, Kraftwerk Güssing, GE Jenbacher	High efficiency electricity production through 3 promising technologies and gas cleaning system.
2006-2008	TU Vienna, Kraftwerk Güssing, GE Jenbacher	Hot gas cleaning system
2007-2009	TU Vienna, Repotec	Interaction FiCFB and methanation + engine

The majority of these projects have finished with the expected results and it is demonstrated with the increases in the number of actors and projects. The continuity and also the intensive efforts from the Austrian actors, pointing out the role of TU Vienna, have been essential in the addition of more international actors and to attract the attention of the European countries involved in BMG. But the main characteristic in Austria is the small number of entrepreneurs leading the sector and in comparison with others, such as Germany, the organization is considered very efficient and looks very promising concerning BMG. This organization is based on Austrian actors, combining private knowledge, with Repotec, and public knowledge, with TU Vienna. This interesting way to assign these two types of knowledge is influencing this function with the collaboration of multiple important actors from other countries interested in BMG. Moreover, the communication and transmission is well done because the scientific knowledge is shared with Repotec. Then, the plant owner Kraftwerk Güssing is in charge of operating this plant.

Looking at heating applications, The Pöls bark gasification project was created in 1987 with the construction of a fluidized (CFB) gasifier that was used in a lime kiln. Afterwards, it produced some problems of contamination in the lime and it was not continuously operated. For this reason and also for feed-in-tariffs, next entrepreneurs were involved in projects related to CHP applications. A great example of this dynamism in BMG is the case of Güssing due to the region demand of energy from renewables, practically based on biomass. Thus, TU Vienna undertook several researches in biomass gasification, building three successful pilot plants during the 1990's. Due to these successful results and also the formation of Repotec after Babcock went bankrupt, the Renet-Austria together with AEE and Jenbacher AG, commissioned a demonstration plant in 2001, under scientific guidance of TU Vienna. The favourable characteristics of this plant and also the use of this concept in further generations of biofuels, encourage the addition of more entrepreneurial actors and multiple possibilities for improving the existing plant.

Naturally, this demonstration project was created in the plant owned by Biomassekraftwerk Güssing GmbH, owner in charge of operating CHP in Güssing. In the same way, other plant owners have been taken part in some BMG projects as it is exhibited in *Table 5-9*.

Table 5-9. Austrian plant owners and manufacturers

Plant Owner	Sector	Involved company
-	Pulp and paper	Lurgi
Alois Hofer	Testing plan	Grübl
Ekkehard Grübl	Pilot plant	Grübl
Kirchmayr Compost & Energy	Waste gasification	AHT Pyrogas
Alois Hofer	Testing plant	Grübl
Biomassekraftwerk Güssing GmbH	District heating	Repotec
Versorgung Niederösterreich AG	Energy/ District heating	AHT Pyrogas + EVN
Kraftwerk Heiligenkreuz Errichtungs-GmbH	Energy/ District heating	Repotec
Verbund Elektrizitätserzeugungs GmbH	Electricity producer	AE Energietechnik

It is interesting to point out the number of owners immersed in energy production and the possible future entrances in this sector.

Looking at another successful plant in Austria, several actors were involved in the "Civitas Nova" project. Moreover, Austria was interested in looking for simple technology designs in CHP applications and then, a small scale plant at Wiener Neustadt was created in 2003. The same actors as in the Güssing plant were involved also in this project. Moreover, the twin fired gasification implanted there, allowed the entrance of new entrepreneurs, as for example the Grübl Austomationtechnic. This company established several wood fixed bed gasifiers for CHP applications in different places of Austria. Consequently, two other entrepreneurs carried out BMG implantations. Firstly, the plant owner Kirchmayr Compost & Energy established a fixed bed gasifier in Saddlet and secondly, a project leaded by TU Graz was translated in a plant in the own university. As it is seen, the development trends have always been in the same direction, CHP applications and the countries involved in other applications, such as Sweden, have been discouraged in that sense.

Following the interest of Austria in developing alternatives in CHP applications, an international consortium built a co-fired plant in the city of Zeltweg. This project was supported by a large number of international companies under the scientific advice of TU Graz. But the non existence of subsidies for electricity production in Austria discouraged further involvements of new actors on this technology development and produced a change in the interest of entrepreneurs.

After the attempts for developing new alternatives in CHP applications and the promising results obtained in the Güssing plant, several projects have been carried out by some actors for high advanced gas usage. It is important to point out the presence of GE Jenbacher in these projects as a supplier of gas engines. This company has intensively participated, supplying fuelled engines and power station generators. Additionally, another important actor is Repotec, designer and promoter of plants in the energy field and environmental techniques. Looking back at other entrepreneurs, Lurgi was producer of non ferruous metals and Babcock was supplier of boilers.

There are some collaborating actors in Austria, particularly; remarking the great labor of reNet, exhibited in *Figure 5-14*. Firstly, Repotec deals with Begas and Ortner, for the construction of small and large scale plants, respectively. Next, Repotec in collaboration with AE Energietechnik, Kraftwerk Güssing and TU Vienna, is considered the foundations of this network. Apart from that, a large number of international companies have collaborated together with this network in some R&D projects but specially, two countries have made an intensive effort. This is the case of Germany with its international University of Stuttgart, participating in the projects AER-GAS and AER-GAS II at the Güssing plant, and Sweden with CHEMREC, involved in the project RENEW. It is remarkable that Finland is practically not involved in Austrian BMG development but the important project "BIGpower" have been a point of union between these two countries. The reason of that can be the difference in the application prime mover, Austria with a gas engine and Finland with an IGCC system. Apart from this, a lot of the companies, Technical Research Centers and Universities from different countries have participated in R&D activities with ReNet but the mentioned actors have had a special involvement in these BMG projects.

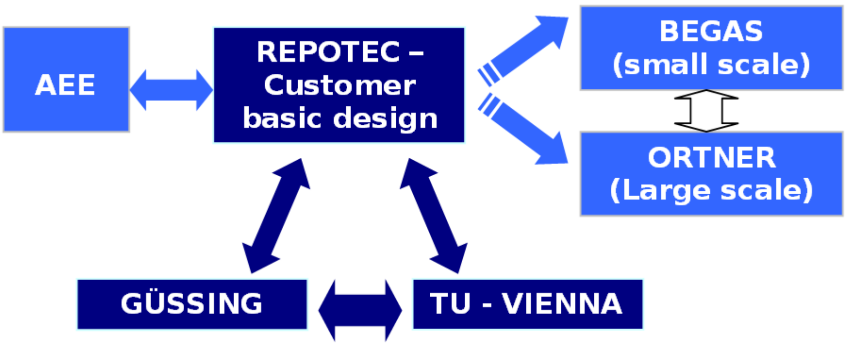


Figure 5-14. Entrepreneurs involved in the Renewal Energy Network in Austria.

Looking at the current situation, the demonstration of a BioSNG poly-generation plant is a promising project in biomass gasification. It is supported by the European Commission and funded by Austria and Switzerland, in Oberwart. The entrepreneurial efforts in the R&D projects initiated in 2004 and 2005 have been gathered by TU Vienna, Repotec, CTU and Paul Scherrer Institute for the creation of this under construction plant in Oberwart. It seems to be the spotlight in whole Europe and a promising development for involving more entrepreneurs in BMG.

To conclude, Austria can be evaluated as qualified in terms of developing BMG and also, it can be defined as organized, internationalized and a point of reference in that sense. Hereafter, the organizational system directed by a small number of actors, it seems to enhance the performance of entrepreneurial experimentation in BMG technologies.

5.5.2 Analyzing the knowledge development and diffusion

As it is mentioned above, biomass plays a significant role in Austria with a considerable percentage of usage in the total energy supply. Moreover, the big amount of wood in sawmills, wood waste and bark make easier the integrity of BMG technologies. This country is making a huge effort regarding Biomass gasification and the support from the European Commission together with the Austrian government promotes its future. The knowledge potential is based on ReNet, an important network where the most involved actors share know-how and other international companies provide experiences in the sector, pointing out Germany and Sweden. In the case of Finland, its important project BIGPOWER has been a point of reference in Austria, concerning biomass gasification development.

Austria can be considered an important promoter of BMG in Europe and its developments have been focused on an important breadth of technologies over the years. After the energy crisis in 1973, the public funding started encouraging the construction of heating plants and during the 1980's, the Austrian Chamber of Agriculture started developing wood and bark furnace in the country. Then so, the first demonstration plant was commissioned in Pöls with a fluidized gasification system (CFB) in a lime kiln. But the contamination problems in the lime discouraged further developments and started focusing on electricity and heat production. This is not the only case of dynamism in BMG developments in Austria; another remarkable fact was the R&D project "BioCoComb" focused on co-fired applications since 1995 by the scientific guidance of TU Graz. This operational plant in Zeltwerg was shut down due to economical reasons and also the lack of subsidies in co-fired technologies for electricity production. Thus, these alternative efforts have provided important insights and experience to further developments.

Greatest efforts have been done in the public sector, pointing out the actuation TU Vienna and Graz. Specially, TU Vienna has been the scientific point of reference in ReNet. The private sector is also important in that sense, as the example of Repotec, introducing wide experiences in new BMG technology developments in the mentioned network. Looking at the international know-how, private knowledge is mainly related to technical supplies and public knowledge to scientific and fundamental bases. Accordingly, these two types of knowledge are well combined but the main characteristic of their involvement projects is the large number of perspectives from different companies, research centers and universities mostly coordinated by German actors. This particular knowledge contribution seems to be the key of gasification evolution and for the other countries a point of reference for enhancing its own knowledge.

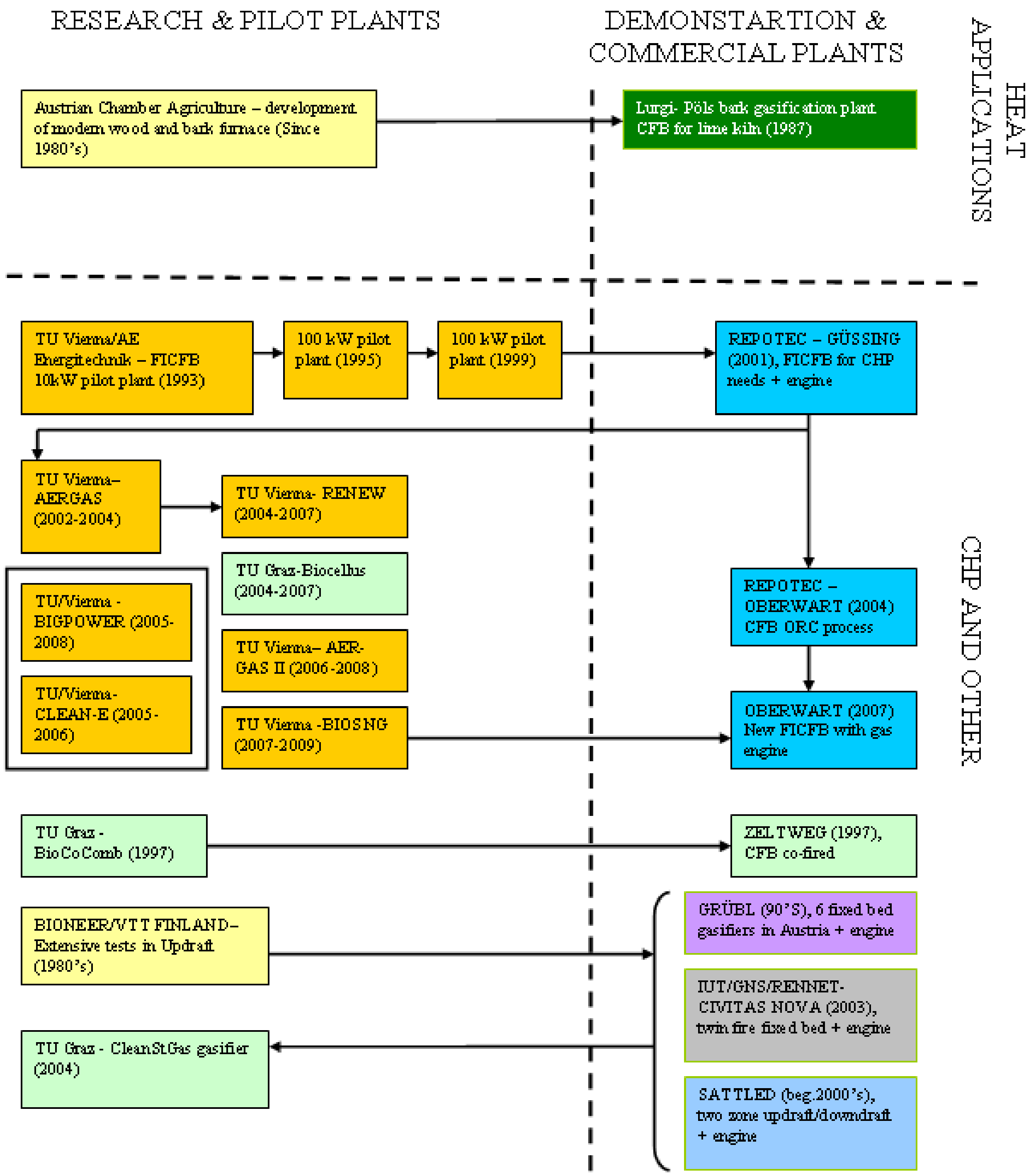


Figure 5-15. Evolution of BMG technologies developed in Austria

As it is seen in *Figure 5-15*, some other projects have been followed a successful learning process, starting with the innovative steam gasification process in 1991. The development of the FiCFB gasification system and the intensive work on different cold models have been translated in the construction of three successive pilot plants in the University of Vienna and produced the commission of the Güssing plant ten years later, in 2001. This plant was constructed to serve the CHP needs in Güssing and delivered a large number of projects focused on synthetic natural gas, Fischer- Tropsch

Diesel and electricity in a solid oxide fuel cell, as it is shown in *Table C-9*, given in *Appendix C*. Moreover, it is still under development and the promising plant of Oberwart, created to accomplish this aim, is planned to be commissioned in a near future.

Knowledge dimension of these projects and its internationality are essential aspects for enhancing the learning process. Thus, more knowledge perspectives help to obtain successful results in BMG. By contrast, if different countries try to focus on different applications and share its knowledge, learning with each other, it could be a good way for enhancing the BMG learning process. Apart of this, most projects have followed an interesting learning process in Austria with the entrance of more and more actors.

Additionally, the fixed bed gasification has also had an important role in Austria due to the interest on simple technology designs in CHP applications at that time. The reason of that was, the need of a new alternative technology for a successful introduction in the market, decreasing operational costs with gas cleaning concepts and enhancing the operation availability of the plant. Thus, the first wood fixed bed gasifiers were introduced in the market proving the future of these simple technologies. This gasification concept was commissioned by Grübl Automationtechnik in different places in Austria, as it is shown in *Figure 5-16*. Moreover, the knowledge acquired by these implementations were transmitted to further innovations, as the project "CleanStGas" at TU Graz with an innovative approach to staged fixed bed gasification and its ideal operating conditions. Additionally, new operational plants were created, such as the one in Civitas Nova and the other in Sattledt, within a twin-fire downdraft fixed bed gasification system. Therefore, there is a clear tendency in energy production but in the case of system components; the cleaning system is the most developed concept. The last R&D projects were focused on gas cleaning methods and also on the production of synthetic natural gas for electricity production.

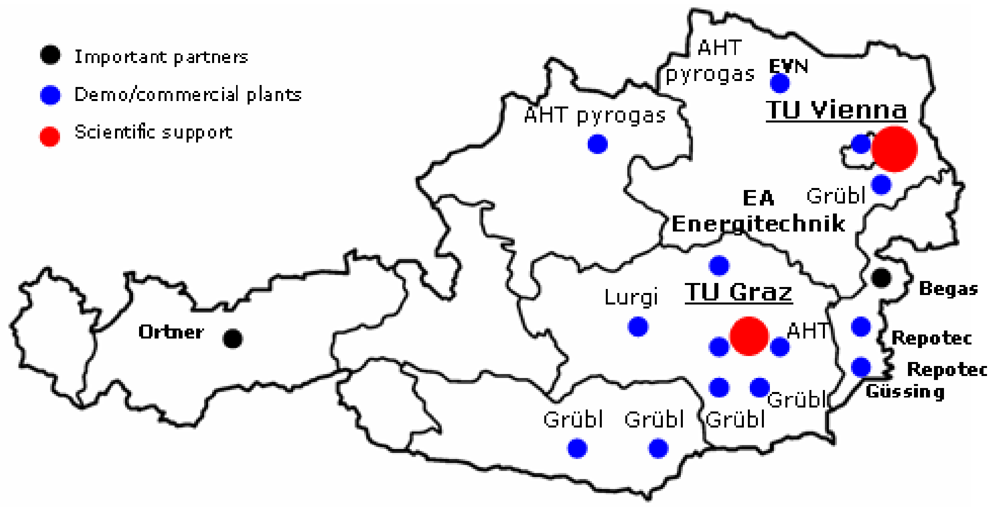


Figure 5-16. Location of Austrian BMG research activities

Furthermore, the great scientific support of the two main Austrian Universities encouraged the R&D activities in the surroundings. Also, the ReNet knowledge diffusion is shared in nearly locations and the following implementations as well. Looking at the international knowledge diffusion, Austria has a different manner of managing know how with only a few main actors involved in BMG. ReNet is doing a great work sharing its knowledge with foreign actors and it is shown in the successful results and the interest of whole Europe in the projects where ReNet it is immersed.

To conclude, the BMG development is strengthening over the years and the effort from Austria and other European countries is enhancing this situation as well. The main feature of ReNet is the well knowledge management and organization, together with the intensive efforts and the learning by doing insistence.

6 ELECTRICITY PRICES PREDICTION AND LEARNING RATES

The use of biomass gasification for power production is, among all the possible applications, the only one that has been continuously developed since the first stages of the development process in all four studied countries. The use of biomass to obtain power is a widespread concept among the industrial community that has been extensively used, mainly through its combustion. Currently, there exist three different paths to obtain energy from this kind of feedstock: combustion, pyrolisis and gasification. However the last one presents a series of advantages compared to the other two more conventional technologies.

Firstly, the combined heat and power generation via biomass gasification techniques connected to gas-fired engines or gas turbines can achieve significantly higher electrical efficiencies compared to biomass combustion technologies with steam generation and steam turbine. Additionally, if the producer gas is used in fuel cells for power generation, an even higher overall electrical efficiency can be attained, even in small scale biomass gasification plants and under partial load operation[7].

Currently, the economical position of BMG is less favourable than combustion based-technologies since BMG technologies are in an earlier phase of development and demonstration. There is a strong need of operating hours to gain practical experience and prove the feasibility of the technology. However, there are some indications that technical advances in developing reliable systems and efficient gas utilization could lead to an economical advantage over combustion. VTT, the national research center of Finland, published, in 2006, some predictions (*Figure A-2*, given in *Appendix A*) about the evolution of the global electrical efficiency and the specific investment cost. These predictions have been used to obtain the electricity price evolution of a small scale gasification-based system compared with small scale combustion–based system. The considered systems have a power

[7] http://www.tab.fzk.de/en/projekt/zusammenfassung/AB49.htm

output of 3MW$_{el}$. During the first stages of this thesis it was considered the possibility to develop this analysis also for larger scale plants of 20MW$_{el}$, which is considered a common size for IGCC power plants. However, the few number of installed plants of this type identified in the database did not allow making a good prediction of the future installed capacity.

The electrical efficiency and the specific investment cost of both studied systems have been calculated by linear interpolation from the data available on the VTT predictions. In the case of combustion-based system it has been considered that due to the technology maturity and its thermodynamic limitations the price will not vary significantly. The results are given below in *Table 6-1*.

Table 6-1. Electrical efficiencies and specific investment cost.

	Year	2010	2015	2020
Gasification + gas engine 3MWel	Electrical efficiency	22,14 %	31,07 %	36,07 %
	Specific Investment	4036 €/kW$_{el}$	2821 €/kW$_{el}$	2214 €/kW$_{el}$
Combustion + steam turbine 3MWel	Electrical efficiency		23 %	
	Specific Investment		3750 €/kW$_{el}$	

Aiming to compare graphically the evolution of these two parameters, *Figure 6-1* and *Figure 6-2* have been plotted. The values for two large scale technologies, IGCC and combustion boiler with steam turbine (both of 20MW$_{el}$), and another advanced small scale application, gasification coupled to molten carbonate fuel cells (MCFC) of 3MWel, have also been included in order to give a more general overview.

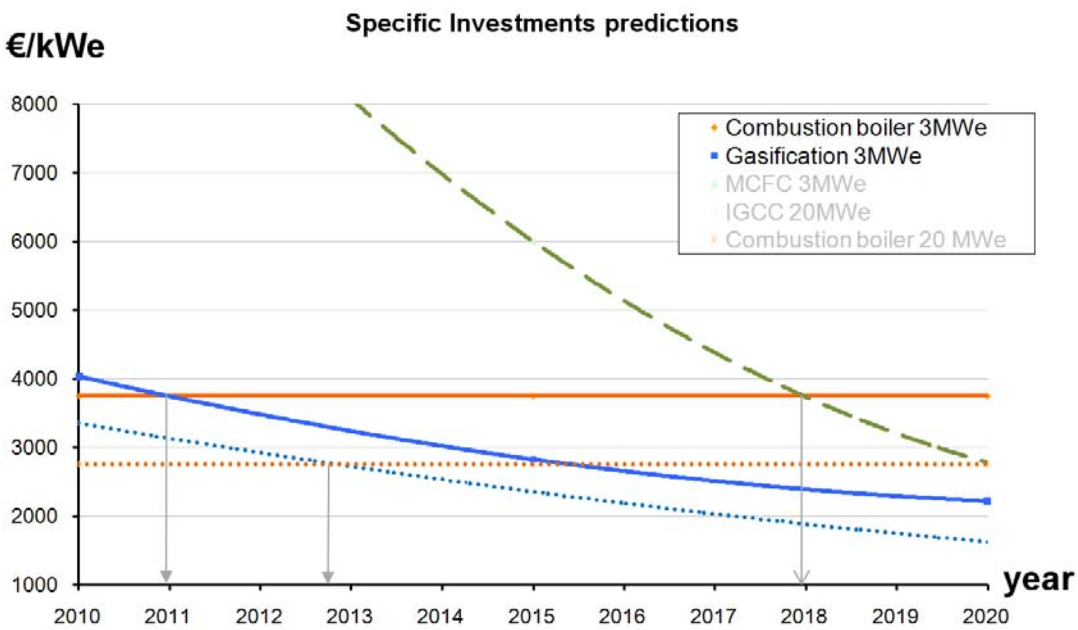


Figure 6-1. Specific investment cost predictions

The previous figure shows that, according to VTT, the investment costs of the small scale gasification system will decrease almost to the half in ten years, equalling the small scale combustion system costs by 2011 and reaching the 2000 €/kW$_{el}$ by 2020. The fuel cell based system has certainly, because of its development status, the highest cost decrease of all evaluated technologies, it will need, however, some more time to become competitive against conventional biomass technologies. Regarding large scale (20MWel) applications, both gasification and combustion, it is worth to say that they show lower investment costs. Nevertheless, gasification-based system, compared to small scale, would need two more years to reach the combustion-based system cost. By 2020 the cost could decrease under 2000 €/kW_{el}.

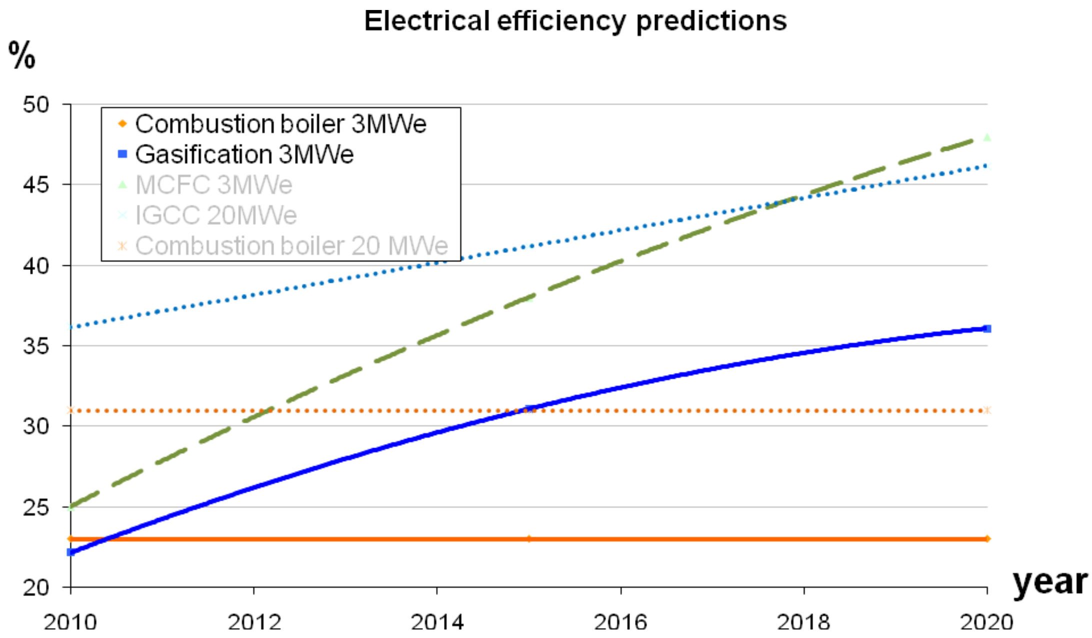


Figure 6-2. Electrical efficiency predictions

The previous **¡Error! No se encuentra el origen de la referencia.** demonstrates that in terms of electrical efficiency gasification based technologies, both at small and large scale, have a considerable advantage compared to conventional combustion technologies. This advantage will increase considerably in the following years. Small scale gasification based systems could reach an efficiency of around 35% whereas large scale IGCC technology could reach an efficiency over 45%. Gasification coupled to fuel cells show the most optimistic trend almost reaching an efficiency of 50% by 2020.

As the predictions presented might be influenced by authors’ expectations or targets, nine different future scenarios will be set before the calculation of the electricity prices. Each one of these will introduce some variations in the presented predictions .The aim is to compare and assess the feasibility of various possible future situations.

Three parameters have been considered for the construction of the scenarios: the global system electrical efficiency, the capital investment cost for the construction of a new plant and the capacity factor (yearly percentage of operational hours). All scenarios contain predictions of these parameters for years 2010, 2015 and 2020, sharing the same point of departure. Hence, depending on whether the scenario is more optimistic or pessimistic, the parameters will vary more, less, or just will not vary at all. The following *Table 6-2* describes the characteristics of the nine scenarios. The complete table with the exact values used for each parameter can be found in *Appendix A* (*Table A-1*).

Table 6-2. Suggested Future scenarios.

Improving factor		**Reduced effect of the improvement →→**	
Efficiency (increasing)	**S1** Efficiency increase	**S2** (in relation to S1) 50% of the efficiency increase	**S3** (in relation to S1) 25% of the efficiency increase
Efficiency (increasing) + Specific investment (decreasing)	**S4** S1 + Specific investment cost decrease	**S5** (in relation to S4) 50% of the efficiency increase + 50% of the specific investment cost decrease	**S6** (in relation to S4) 25% of the efficiency increase+ 25% of the specific investment cost decrease
Efficiency (increasing) + Specific investment (decreasing) + Capacity factor (increasing)	**S7** S4 + capacity factor increase	**S8**(in relation to S7) 50% of the efficiency increase + 50% of the specific investment cost decrease + 50% of the capacity factor increase	**S9** (in relation to S7) 25% of the efficiency increase + 25% of the specific investment cost decrease + 25% of the capacity factor increase

Once the scenarios have been presented, the next step is the calculation of the electricity prices using the evaluation basis presented in the methodology section. The results obtained are presented in *Table A-1*, that can be found in *Appendix A*. At the same time, the data collected in the database from the gas engine power plants has been used to predict the future installed capacity (*Figure A-6* in *Appendix A*) in order to plot the learning curves (*Figure A-3*, *Figure A-4*, *Figure A-5* in *Appendix A*) by interpolating through a power trend line as it is explained in the methodology. With the learning curves plotted it is possible to obtain the learning rate for each of the nine scenarios. The final results are presented in the following three figures (*Figure 6-3*, *Figure 6-4* and *Figure 6-5*) where the electricity price variation curves are plotted jointly with the learning rate of each scenario.

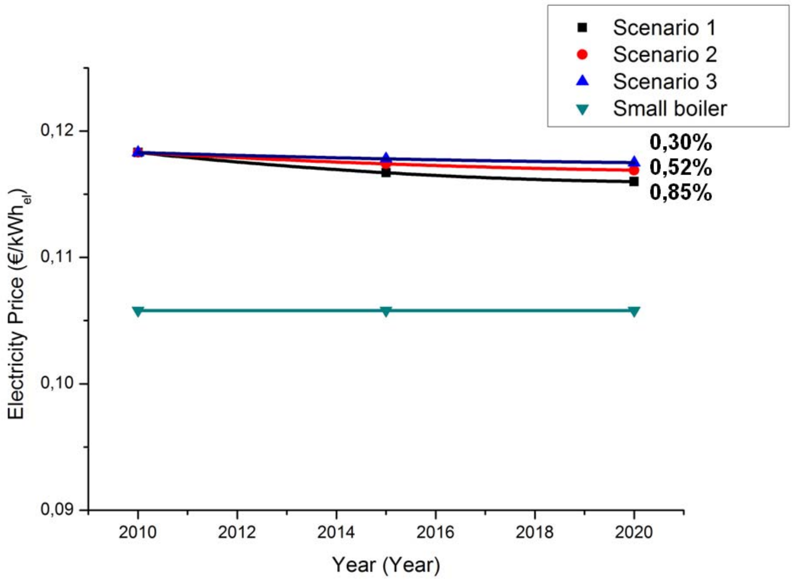


Figure 6-3. Electricity price decrease and LR, varying electrical efficiencies.

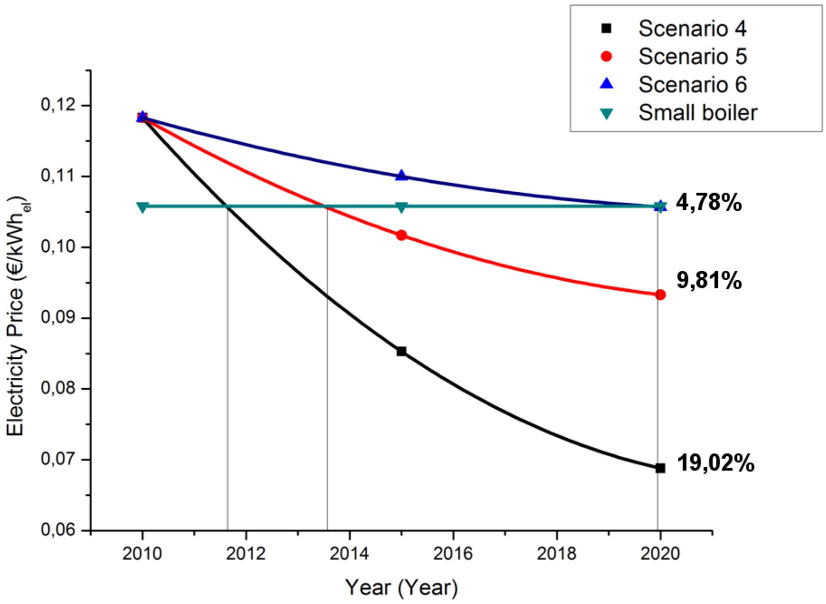


Figure 6-4. Electricity price decrease and LR, varying electrical efficiencies and plant costs.

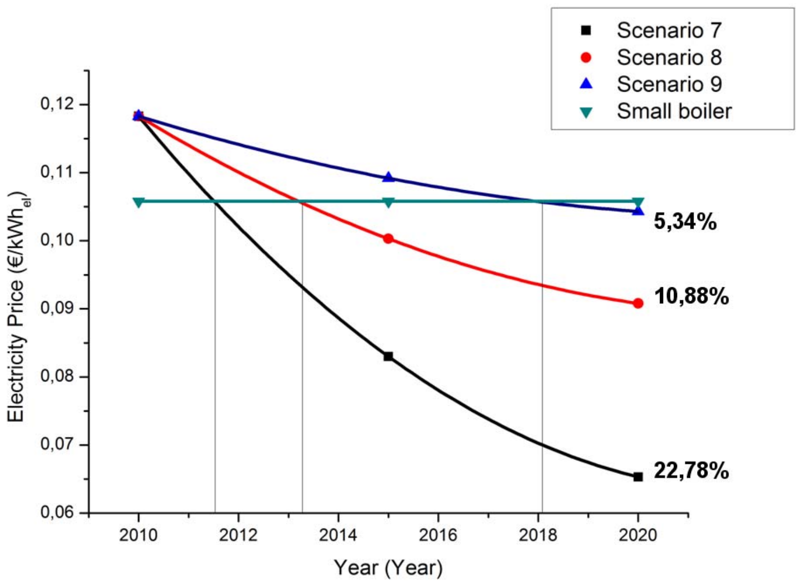


Figure 6-5. Electricity price decrease and LR, varying process efficiencies, plant costs and capacity factor.

When using our database to predict the future installed capacity in order to calculate the learning rate, it is important to point out that there are some factors that could have modified the obtained results. Some of these are the experience acquired from other plants not considered in the data collection, plants shut-down after some years of operation or the fact that the study has taken into account plants of all different scales.

Taking these considerations into account, the pictures show that the most determinant factor in order to become competitive is the reduction of the initial investment costs. Neither of the first three scenarios, where the only factor that have been changed is the global electrical efficiency of the plant, have achieved prices below 0,1058 €/kWh$_{el}$ which is the price calculated for conventional combustion technologies. On the other hand, when the initial plant costs decrease, even at 25% of the VTT predictions (scenario 6), the electricity prices achieve competitive values within a period between one and eight years. This fact stresses the importance of standardization. Currently, there are several actors developing research activities aiming to optimize the efficiency of the process. However, the technology will not reach a commercial stage until the actors' community makes some efforts in optimizing and standardizing the system manufacturing process. This is strongly connected with the learning-by-doing process, which is unfolded when new demonstration and commercial plants are built.

Additionally, if the capacity factor of the plant increases over the constant 85% rate considered in the evaluation basis, its influence in the electricity prices is weaker than the investment costs. However, the lower is the decrease of investment costs the higher is the influence of the capacity factor. For instance, scenario 9, with an investment costs reduction of 25% in relation to VTT predictions and a the capacity factor growing from 85% to 86,25%, needs two years less to achieve the 0,1058 €/kWh$_{el}$ compared to scenario 6, with the same investment costs reduction but without capacity factor growth. This fact highlights the potential of the learning-by-using process once the technology has achieved certain stability in the capital cost of new plants.

Regarding the installed capacity, most of the scenarios show that it should be at least doubled in order to reach competitive prices. In the database an accumulated installed capacity of 87,37MWth was registered by 2008, including plants from the whole range of scales. The less optimistic scenario (S6), without considering the first three where the technology is not competitive in the short-run, shows that an installed capacity of around 500 MWth is needed to achieve competitive prices by 2020. That means 412,63 MWth installed between 2008 and 2020, which would correspond to 138 plants of 3MWth built within 12 years. According to the most optimistic scenario (S7), an installed capacity of round 145MWth would be needed to reach competitive prices between 2011 and 2012, which would require 57,63MWth installed between 2008 and 2012, that is 20 plants of 3MWth built within 4 years.

In like manner, scenario 8 would requiere 40 plants built within 6 years, which corresponds to approximately 7 plants built each year.

The most optimistic scenario (S7) achieves an electricity price of 0,0653 €/kWh$_{el}$ by 2020 which means a reduction of almost 50% in relation to price predictions for 2010, with a value of 0,1183 €/kWh$_{el}$. The combustion-based technology price is reached between 2011 and 2012. Considering the predicted installed capacity of similar systems, this would mean a learning rate of 22,78%, i.e. the electricity production cost would suffer a reduction of 22,78% when the installed capacity is doubled. This rate would be obtained considering the following facts:

- A system electric efficiency increase from 21,42% to 35,71%
- A plant capital cost reduction of 45% from 4036 €/kW$_{el}$ to 2214 €/kW$_{el}$
- A capacity factor increase from 85% to 90%, which means 438 operation hours more per year.

Meanwhile, a less optimistic scenario such as the eighth achieves a price reduction of approximately 24% reaching an electricity price of 0,0908 €/kWh$_{el}$ by 2020 and reaching the combustion price between 2013 and 2014, two years after the seventh scenario. This would mean a learning rate of 10,88% determined by:

- A system electric efficiency increase from 21,42% to 28,57%
- A plant capital cost reduction of approximately 23% from 4036 €/kW$_{el}$ to 3125 €/kW$_{el}$
- A capacity factor increase from 85% to 87,5% which means 219 operation hours more per year.

The comparison between those two different scenarios suggests that the use of a general "rule of thumb" learning rates of 20% coming from the observed rates for many electricity generation technologies, as it has been seen in the methodology section, might be too optimistic in the case of BMG gasification technologies. Considering the current trend, these learning rates assume advances difficult to achieve. This is also the case of the fourth scenario, with the same assumptions as VTT concerning capital cost and global efficiency, that turns out to be the second one in terms of optimistic expectations. With a learning rate of 19,02%, it expects a price reduction up to 0,0688 €/kWh$_{el}$ by a 45% reduction of the capital cost and an increase of the efficiency up to 35,71%.

In fact, the current number of changes introduced in the system components, especially in the cleaning systems and the gas utilization components, makes it difficult to think about a close standardization stage before the demonstration of fuel cells and microturbines, which are still in early stages of development. These new technologies will allow reaching electrical efficiencies up to 45% according to various researchers, although, due to the coexistence of various different CHP systems, a redistribution process of the technology used in each scale will be required, slowing down the standardization process.

Moreover, plant cost reductions of more than 30% would require the installation of tens of plants, according to some predictions (see *Figure 6-6*), and without a definite niche application this appears to be still out of range.

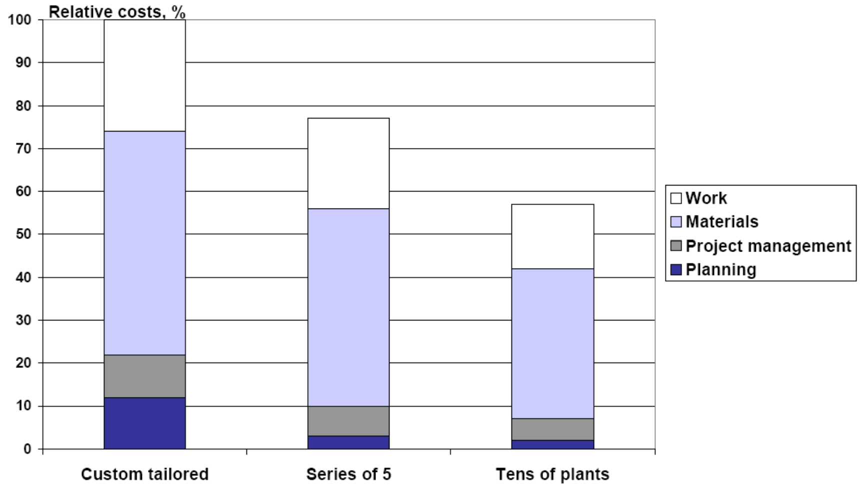


Figure 6-6. Possibilities for cost reduction of small BMG plants using different series production methods
Source: Wärtsilä Biopower, Jussi Heikkinen
http://www.iea.org/Textbase/work/2003/extool-excetp6/III-hely.pdf

Regarding the increase in the capacity factor through a growth of the yearly operational hours, it appears to be quite optimistic to think of capacity factors around 90% while in successful CHP demonstration plants like Güssing (see *Figure 6-7*), capacity factors of more than 80% have not been reached yet. In fact, achieving more than 7500 hours of operation per year, i.e. a capacity factor of 85%, is still a problem for the great majority of small scale gasification systems.

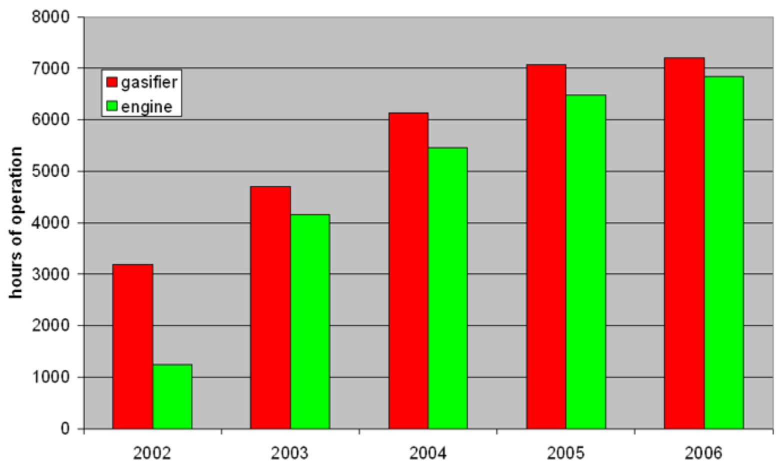


Figure 6-7. Yearly operational hours of Güssing CHP gasification plant.
Source: http://www.ficfb.at/renet_d.htm

In conclusion, positive expectations on the future performance of the technology are largely justified by its promising potential. This fact, jointly with the social acceptance of other biomass based technologies, has pushed some institutions, like VTT, to make predictions about the future commercialization possibilities in terms of electricity prices. In some cases, these forecasts have been done from a rather optimistic point of view, aiming to boost the technology reputation. It has been seen, however, that the prices offered by combustion technologies are achievable, but only if the governments give suppliers icentives for building more plants and increasing the operational hours. Following this, a quantity of seven new plants of $3MW_{el}$ should be build each year, according to one of the scenarios considered feasible. Nonetheless, current development trends make it difficult to think that BMG technology will reach competitive electricity prices before 2012 whereas it seems much more feasible to do so by 2020, even for the less optimistic expectancies. Moreover, the majority of the predictions show that prices will continue decreasing after 2020, some of them forecasting prices below 0,1 €/kWh_{el}.

7 IDENTIFIED STRENGTHENING AND WEAKENING FACTORS

After the analysis of the functions it is clear that their performance has been quite different in all four countries. The final contribution of each function to the development of the technology has varied as well. It would be a mistake to compare them without considering the particular characteristics of each country, as these characteristics will enhance or reduce the efficiency of these functions and, of course, make it more or less easy to develop them. However, having a global overview of all factors together can be helpful in order to know what should be improved or as a reference to regard. Moreover, sometimes it is easier to identify those weak points of the system by comparing it with another one that is performing better.

Thus, the aim of this chapter is to identify, from the analysis undertaken in each of the four countries, those factors that boost or make difficult its performance. These will be called respectively *strengthening* and *weakening factors.* This analysis has been carried out separately for both studied functions. As consequence of the strong connections between them, some very similar factors will be presented. Nevertheless, it makes sense since, as it has been stated by Bergek (2007), "*Functions are not independent, but rather tend to reinforce each other*". With the aim to simplify the analysis and highlight the relation among some of the presented factors, these have been grouped according to how they influence the performance of the function. At the same time, these have been classified in three different categories according to their positive, negative or "double-edge" effect. The latter refers to those factors whose goodness or badness depends on the characteristics of the technology innovation system.

7.1 Factors affecting entrepreneurial experimentation

As it is seen in *Figure 7-1*, there is a large amount of factors reinforcing and weakening entrepreneurial experimentation. The difference between each other is the level of influence generated in this function, concerning the number of countries affected or the potential impact in the own country.

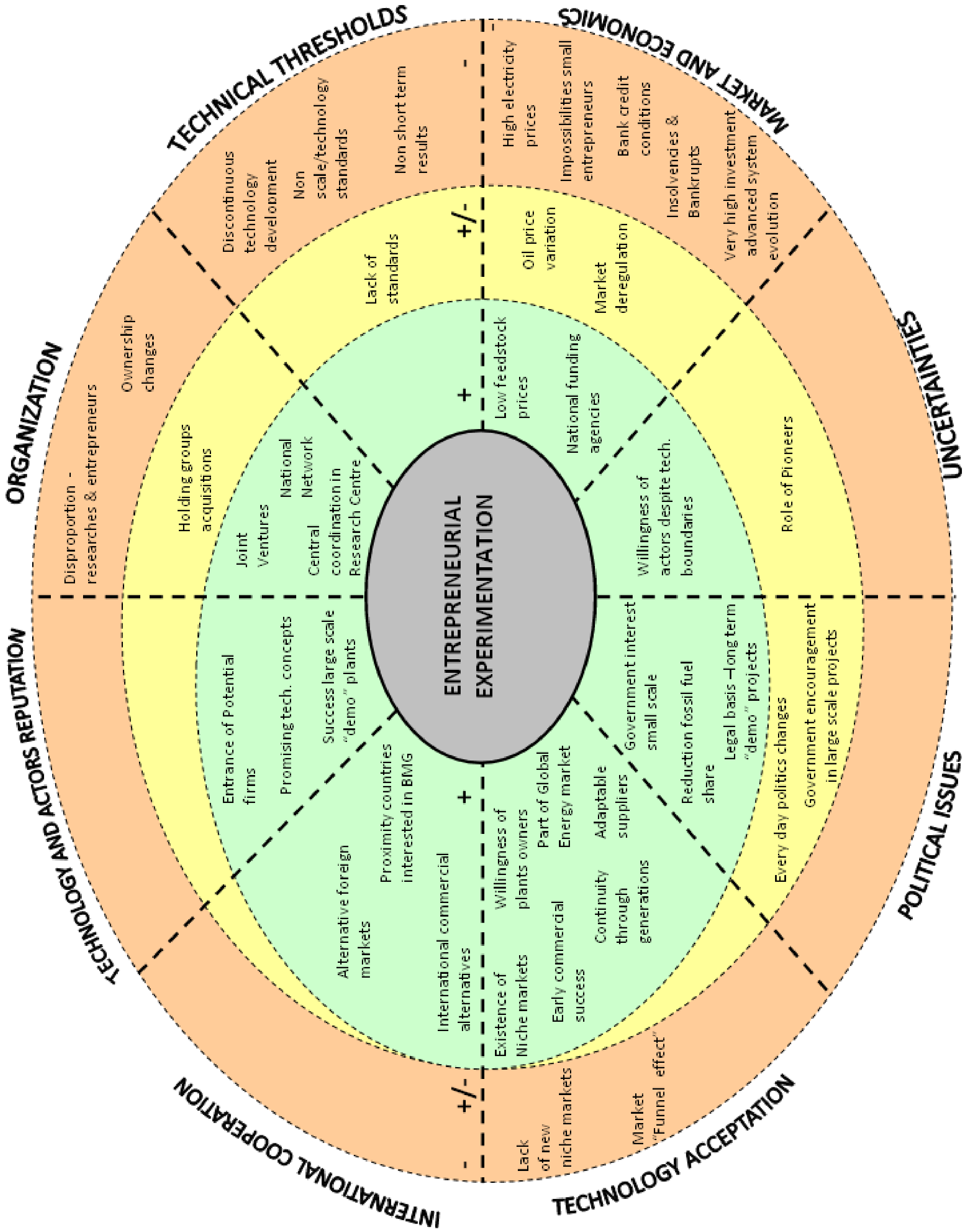


Figure 7-1. Identified factors affecting Entrepreneurial experimentation

As a starting point, “market and economic” issues are influencing critically in entrepreneurial experimentation, but not positively. Most of these factors discourage the entrance of entrepreneurs in BMG. The high electricity prices, in comparison with combustion technologies, bring up certain doubts in the economical feasibility of this technology. As it is shown in the learning curves analysis, the electricity prices in BMG are decreasing over the years but currently, it can not be compared with state of the art technologies. However, the increases in the fuel prices, such as coal, encourage the biomass usage and it converts BMG in a promising technology. Moreover, the commercial application of biomass gasification involves important initial investments that small entrepreneurs can not undertake and are forced to get bank credits. The main problem of that is the uncertainty created in banks due to the number of BMG plants shut down for economical reasons. But this fact is not only affecting to bank’s confidence, but it is also affecting to all kind of entrepreneurs due to the high risk of failure. Apart from that, entrepreneurs have to take charge of high costs due to advanced requirements in the scale up process and improvements in the plant efficiency. Conversely, some other factors are influencing in a double-edge point of view as the case of market deregulation. This reduction or simplification in the electricity market restrictions creates twofold consequences in entrepreneurial experimentation. On the one hand, this process mainly consists of encouraging the efficiency operation of markets and generating more freedom among entrepreneurs; but in the other hand, the market competitiveness triggers a difficult entrance for small entrepreneurs. Moreover, the oil price variation is affecting not only biomass but also other renewable resources. Exemplifying the encouraged part of this factor, the oil crisis in 1973 was an inflexion point in BMG and the concerned countries responded with numerous initiatives to reduce further dependency. Additionally to these double-edge factors, the energy demand affects to entrepreneurs due to the changes over the time. Thus, considering heat, electricity and fuels as the main types of demands; the technology development level for these applications will never be as good as expected due to several changes. Finally, there are some other important factors that are encouraging entrepreneurial experimentation in these four countries. As it is known, the large quantity of biomass resources, such as wood, encourages greatly to enter in this sector but the need of financial resources is always there. For that, in some countries, such as Finland and Sweden, there are national funding agencies financing R&D projects concerning BMG technologies.

The “technology acceptation” in the market has been affecting somehow positively. The existence of niche markets has encouraged actors to be involved in BMG and plant owners have taken advantage of this opportunity as well. This is the case of district heating and energy supply markets in Austria and Finland; and niche markets related to the transport sector, in Sweden and Germany. Following with this, sometimes different generations of technology have been used in a plant within the same industrial process. A good example of that is Sweden with the company Chemrec, as it explained in the above sections. There are no doubts that the creation of these niche markets, such as pulp and paper, enhances the degree of technology specialization, reducing uncertainties and risks in entrepreneurs.

Additionally, pilot, demonstration and commercial plants need the integration of different apparatus in the system and suppliers have the chance to take advantage of that, supplying boilers, gas engines, feeding and gas cleaning systems, etc. Thus, the creation of these types of plants encourages the entrance of suppliers in the sector.

Moreover, it is worth to point out the importance of biomass is some countries, such as Austria, covering an important part of the entire primary energy demand. Thus, most national entrepreneurs are encouraged due to this fact and also because it is supported by the own government. Additionally, the early commercial successes of this technology influence entrepreneurs, as it is seen in Bioneer gasifiers. These gasifiers were implanted in different places of Finland and also of Sweden, creating an important technical base for further entrepreneurial actors and encouraging the development of BMG technologies in the own countries.

Concerning weakening factors, often the countries often focused their R&D projects on a specific market and all the implantations are related to this development line. The lack of new niche markets is a common characteristic of all the countries and it discourages the entrance of actors involved in others types of markets. In addition, the competitiveness of the market is a big deal for small entrepreneurs due to the created “funnel effect”. In this market where the uncertainty is very high and barriers to entry very low, a lot of entrepreneurs start undertaking projects but only the most competitive ones go ahead.

The “Organization” among actors also influences in various directions entrepreneurial experimentation. Some important factors are affecting positively in this function as for example, the integration of a Research centre controlled by the government. This is the case of Finland, with VTT, that coordinates the majority of projects created in the country. This actor is responsible for managing know how and further implementations. Thus, this fact encourages entrepreneurs, enhancing the security of its actions. But this is not the unique remarkable organization in that sense because strong networks have been formed with only a few actors, as the example of Austria, where public and private entrepreneurs have collaborated together. In another particular situation, several R&D projects have been undertaken by actors, forming joint ventures and intensifying the efforts in the referred development or implementation. These types of connections enhance the willingness of actors for entering the sector. As a double-edge factor, well known holding groups are acquired by smaller entrepreneurs; allow gaining an important support for entering in BMG. But on the other hand, other entrepreneurs have been affected by this strong competition. Following to weakening factors, several organizational changes have appeared as the remarkable example of Sweden and Finland, with Chemrec and Bioneer respectively. Moreover, it is seen as an important disproportion between the number of researches and entrepreneurs. Thus, the results in the majority of researches were not applied and this fact discouraged the intensity of further investigations.

The “political issues” are always affecting these types of technologies and the potential of biomass does not pass unnoticed through governments. The government actions are essential for the future of BMG, as these shows in Germany with the establishment of a legal basis that encouraged actors for undertaking long term demonstration processes. Other actions as the short term targets to reduce fossil fuel usage, in Sweden, encouraged the entrance of entrepreneurial actors as well. Moreover, other decisions are related to the technologies themselves, as the interest of Austria in introducing simple technology designs for enhancing the operation availability of the plant and decreasing operational costs. It encouraged entrepreneurs to undertake small scale applications in that respect. But sometimes it is not a usual feature, most entrepreneurs are focused on large scale projects, as Kari Salo said: “*I can only see a very few of them and has decided to only bother with plants larger than 10MWth”*. There are no doubts that it benefits BMG but small scale applications can remain in the background. By contrary, political decisions can influence negatively in entrepreneurial experimentation. The funding given by the government can change from one program to another and this creates certain doubts among entrepreneurs.

The “technical thresholds” restrain the experimentation continuity and also creates uncertainty among entrepreneurs. The huge amount of technologies and applications can complicate the standardization of the system and sometimes entrepreneurs are uncertain in that respect. However, the large number of possibilities in BMG allows entrepreneurs to enter in different markets. The lack of standardisation is a big problem because it generates complexity in the system. As it is known, there is a huge diversity of technologies applied in plants with different sizes and somehow, it makes technology development more difficult to be enhanced. Moreover, the technology development in BMG has suffered important changes over the years and the continuity of these developments from pilot to commercial plants is not usual. Thus, entrepreneurs are really afraid and can be discouraged by this technical threshold.

The “international cooperation” is an important factor for the integrity of BMG and the active collaboration between these four countries always encourage the entrance of new actors. As it has been shown, the proximity of Finland and Sweden on the one hand and Austria and Germany on the other has encouraged the collaboration within the countries but there are also interactions between all of them. Moreover, the lack of a specific market in one country can be covered by the existence of it in the other countries. Hence, the possibilities created abroad encourage the entrance of international actors.

The good “technology and actor reputation” influence in terms of producing less uncertainty in new entrepreneurs. Thus, the entrance of potential firms with large experience in other energy sectors encourages the entrance of new less prestigious actors. Concerning technologies, the promising technology concepts are always in the spotlight of actors and it is the same situation for new entrepreneurs looking at BMG with certain doubts. Additionally, the successful results in large scale demonstration concepts remove also uncertainty in BMG technologies.

Finally, “uncertainties” and doubts are continuously arising in the above factors all over the time but some of these are related to the entrepreneurs’ role. Often, taking the role of pioneer is difficult due to all the factors mentioned above but mainly because it can produce a huge loss of money. Moreover, the risk is incremented when the initial failures appear and then, the willingness from entrepreneurs plays an important role in that sense.

7.2 Factors affecting knowledge development and diffusion

Similarly, knowledge development and diffusion is also affected by a number of factors, as presented in the following *Figure 7-2*.

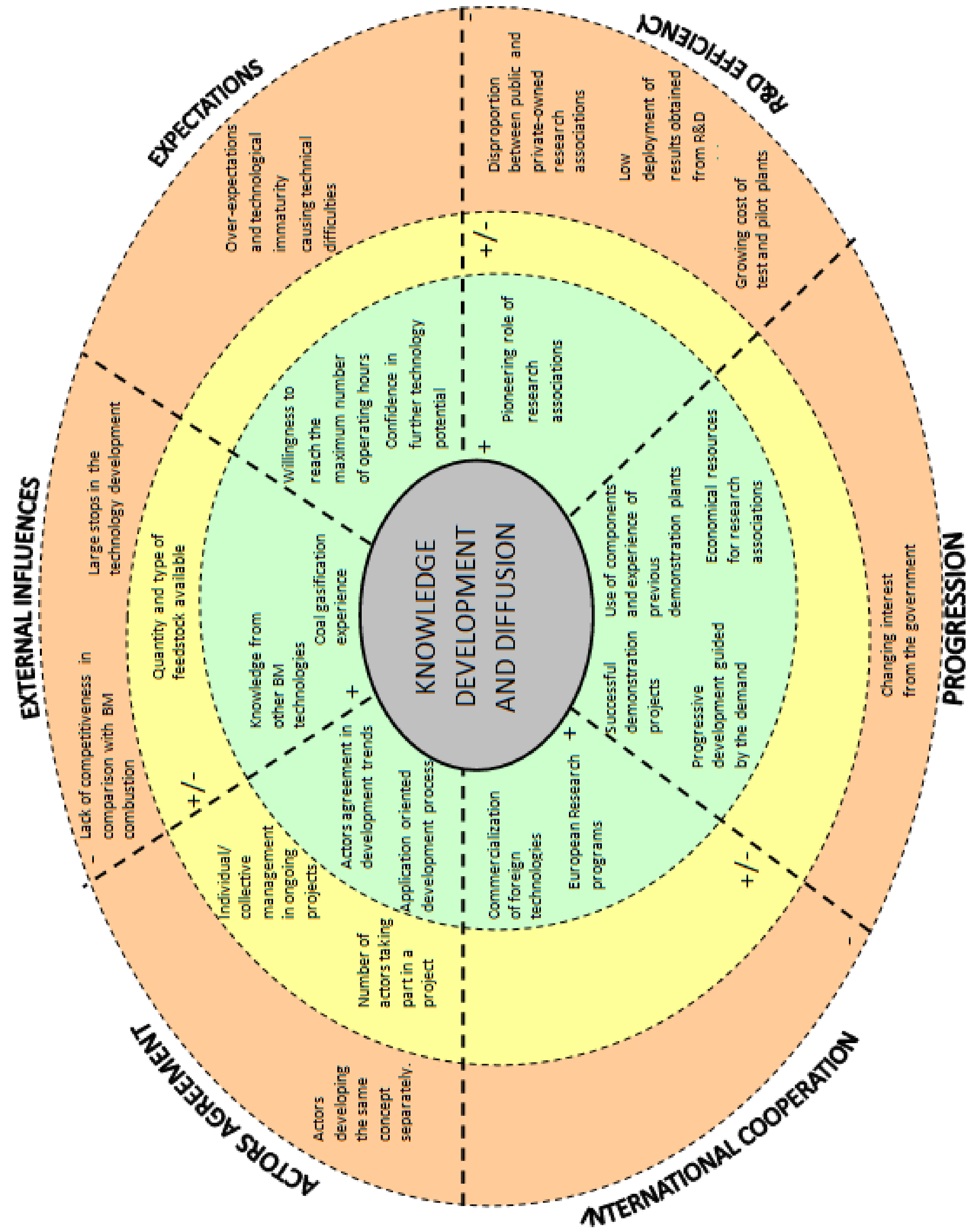


Figure 7-2. Identified factors affecting Knowledge development and diffusion

Concerning the *knowledge development and diffusion* the first group of identified factors has been called *external influences* considering the influences created by other technologies, and the geographical, historical and political characteristics of each country. Two important complements that have enhanced the knowledge base of the biomass gasification since its early stages, have been identified. On the one hand there is all the experience gained in the gasification of coal since the first production of gasified coal gas for lighting purposes in the 1850's. The empirical approach and the scientific fundamental research became an important support during the early stages of development of BMG. Germany is the one among the four studied countries with more experience in that field. On the other hand, there is all the experience gained from the use of biomass trough "low efficiency" routes, these are combustion and pyrolisis, much better known for a long time, both technically and commercially. In the end, gasification comprises both processes in its stages. Therefore, there exists system components used in both technologies that does not need to be reinvented, just modified in most cases. Nonetheless, the existence of this alternative biomass based technologies has reduced the experience acquired through the construction of new plants, i.e. learning-by-doing, since BMG still can not compete in terms of prices.

Additionally, there have been some other factors that have badly influenced the knowledge development. Among these, the most remarkable are the large stops in the development process caused by several reasons, such as changes in the demand or changes in the political interests. When the process is interrupted for a long time there is a high likelihood to leave behind some of the knowledge acquired in the past, losing an important source of knowledge and experience. The availability of the feedstock, in terms of quantity and type, has hardly conditioned the development direction too, creating a strong dependence in the reactor design, as well as the feeding system design. Feedstock types like waste or straw have required developing new feeding systems, creating interruptions in the development process of gasification reactors.

Secondly, it has been identified a group of factors affecting the *progression* of the development process. The formation of a solid knowledge base requires a step-by-step process, with actors trying to maximize the experience acquired from every stage. When one of the stages is skipped or underestimated then the next stage might suffer from a lack of experience causing failures in parts of the system that were supposed to work properly. In this regard, when technology development is pulled by a progressive demand, in terms of requirements on system performance, it is easy to take the maximum advantage of every stage in the process. Otherwise, when the demand shifts rapidly from less to more advanced applications the development will be pulled "aggressively", leaving behind some important knowledge sources. Apart from the market demand, the government interest can also produce the same effect, in some cases being even more influential.

One of the most critical moments in the development process is the scale-up from pilot plants to commercial plants. It is crucial that researchers have enough economical resources to test the results obtained in fundamental research in pilot plants. If they do not, suppliers will be fully responsible to build and operate pilot plants. This will create a gap in the process development, forcing researchers to look for a supplier to deploy their results. This dependence relationship will slow down the process and in some cases interrupt it, if suppliers do not take the initiative to collaborate.

Other factors like the success of demonstration projects and the development of successive projects using the same facility, such as Värnamo plant or Güssing, will help to not over-accelerate the development process putting more emphasis on the results obtained and on how to make use of them to reinforce the acquired knowledge.

The intensity of *international cooperation* is a determinant factor in the diffusion of the knowledge. In some cases this is promoted by political institutions through various funding programs and in other cases it is just the initiative of some suppliers to enter foreign markets in order to expand their commercial possibilities. In both cases, it will create positive relations among suppliers and researchers necessary to share the knowledge and avoid the existence of parallel knowledge development, i.e. various actors developing separately the same concept making an inefficient use of human and economical resources.

Apart from the cooperation of all actors taking part in the technology development it is important that they all agree about the development trends, concerning future applications and system concepts. This *agreement* is also essential from the point of view of gas utilization system suppliers since a standardization of the gasification system would lead to more accurate design specifications as well as to a higher degree of confidence. If different gasifier suppliers focused their efforts on one singular application, the likelihood that other entrepreneurs decided to integrate the technology in their process would be higher. Also the specialization in the knowledge development trends will lead to more mature final designs. Even so, reaching an agreement could be more or less difficult depending on the number of actors taking part and the management style of projects coordinators.

Actors' *expectations* and determination when developing the technology condition strongly the performance of the function too. The learning-by-using process is strengthened when actors show willingness to reach the maximum number of operation hours. Even when the final results of demonstration projects are below the initial expectations, it is important that the facilities continue being operated and accumulating working hours. These will turn directly into operating experience, something really necessary to reach a commercial success. In this sense, it is quite necessary that actors work thinking about the global community profit and not only from an individual perspective. Additionally, it is also important to make use of the experience gained from mistakes and failures, i.e. learning by failure. Sometimes, after the failure of a plant or project, it is necessary to be patient and wait the technology to mature through other paths, keeping the previous knowledge available for a further use. Maintaining this knowledge base, without leaving it behind, depends on suppliers' commitment towards the technology potential.

The last factor but not the least, is the *efficiency of R&D activities*. The role played by academic researches overcoming the first technological uncertainties through fundamental research is crucial in the development process. Usually, research associations work under a lower degree of pressure than commercial suppliers. Because of this, it is important that they assume a pioneering role. Nonetheless this is only possible if they have enough economic resources. One factor that have affected the potential of R&D associations is the growing investment costs of pilot plants for advanced applications, mainly due to the addition of new system components related with gas cleaning. This price rise, combined with a low deployment of the results obtained from research, has reduced considerably the efficiency of this knowledge development resource. It is also important to maintain a proportion between public and private-owned research associations, since both of them present different advantages. On the one hand, public associations reinforce the diffusion potential of the results and, on the other hand, private-owned work closer to commercial suppliers developing more process commercial oriented activities.

As a conclusion of this chapter, the current status of both functions is not due to a unique cause, but due to the combination of various different factors affecting them. Some of these factors are affecting both functions at the same time, which demonstrates the strong connection between them. After analysing all factors, these could be classified in two main categories: “controllable” and “uncontrollable”, depending on if actors’ community have the possibility to control them. Historically, the “uncontrollable” have demonstrated to be the most influential ones, although its influence has varied throughout history. In those periods in which the repercussion of negative “uncontrollable” factors have been minimum, actors’ community have not been able to take advantage of the positive “controllable” in order to boost the technology development. This has been mainly due to a lack of operation experience in the knowledge development and a lack of confidence from entrepreneurs. In this sense, connecting with the previous chapter, if the government creates incentives to build new plants instead of boosting the demonstration of new applications, this will give the technology the opportunity to demonstrate its worth. However, currently, actors’ community seem much more focused on large demonstration projects. These kinds of initiatives can help to restate the potential of the technology, but unless they come together with projects that demonstrate its operational feasibility, BMG will never have enough resources to demonstrate its competitiveness. Once the technology has shown that is both promising and feasible, those factors which were not influenced directly by the construction of new plants, such as firms organisation or cooperation, would finally be influenced indirectly throughout the reputation gained. Finally, this could lead to a likely commercial success.

8 DISCUSSION AND CONCLUSIONS

The primary aim of this thesis was to *analyze the knowledge development and diffusion patterns of the biomass gasification technology since 1970's in Austria, Finland, Germany and Sweden*. This analysis began with a brief study of the BMG fundamentals and a global assessment of the current state-of-the-art in the mentioned countries. Following this, two functions of the innovation system approach were selected as a framework for the analysis. These were Knowledge development and diffusion and Entrepreneurial experimentation. Some indicators were used to analyse and assess the performance of these two functions from a country perspective. The results of this primary study were put in common in the second part of this thesis, which had the aim to *identify factors that strength or weaken the previously defined functions*. Finally, a *numerical assessment of the rate of learning in small scale biomass gasification for electricity generation* was carried out, aiming to make some predictions about what is the likelihood for the technology to become competitive in the short term.

Currently, the four studied countries show a great degree of involvement in BMG development activities. This has been demonstrated by the growing number of demonstration projects undertaken. However, both the continuity and the direction of the development process show several differences from one country to another and consequently, the current state-of-the-art differs quite a lot. In fact, before the 1970's, each country investigated separately with very few international connections. Later, thanks to European research projects, a higher level of collaboration has been achieved.

In the case of Sweden and Finland, geographical and political similarities, jointly with the broad experience gathered in wooden combustion boilers, were the most important factors in the early phases of development. Thus, this previous knowledge was used to develop medium scale gasifiers for district heating applications. At the same time, the pulp and paper industry encouraged the development of large scale BMG gasifiers for lime kilns. After several successful commercial projects, both countries followed different development lines. On the one hand, Sweden took advantage of this niche application and continued developing black liquor gasification through Entrained flow gasifiers, combining fuel and electricity production. On the other hand, Finland oriented its development in CHP applications, focusing mainly on gas engines with small scale fixed bed gasification and afterwards, on large scale BFB gasifiers with an IGCC gas utilization system.

At the same time, in Germany and Austria, the development of heating applications got blocked due to a number of failed projects, a lack of niche markets willing to integrate the technology and the influence of the new EU directives. These three reasons, led to a change in the development direction, concentrating on more advanced applications. In this way, Austria focused its research activity on the development of gasification coupled to gas engine, coming up with a new generation of CFB technology. Likewise, Germany, with an important number of research centers and a large experience in coal gasification, opted for large scale biofuel production combined with power production through IGCC systems. Various research projects on small scale advanced applications were also started jointly with other countries, with Austria as the strongest collaborator. It is worth to remark as well the accumulated experience in waste gasification after various thousands of accumulated operating hours in large scale plants. The quantity of resources invested lately in development activities by both Germany and Austria, lead to foresee tangible results in the short-term, which would turn both countries again into a worldwide reference in terms of advanced BMG applications.

It is also worth to stress the influence exerted by the success of some large scale projects in the technology diffusion. These have undertaken not only demonstration activities but also commercial, boosting at the same time further research activities. This is the case of Güssing (Austria), Värnamo (Sweden), Schwarze Pumpe (Germany) or Lahti (Finland), all of them characterized by a large number of operation hours. Another notable source of diffusion is the research programmes funded by the European Commission named Framework Programme, which have motivated the collaboration among actors of different countries in common projects. Germany, Sweden and Austria are three of the countries with greater involvement in these type of international projects.

Regarding the entrepreneurial experimentation, two organizational models have been identified in this thesis. The first one is characterized by its reduced number of actors with a high degree of organization and collaboration among them, which is the case of Austria and Finland. Austria is organized by a network in which public and private associations participate and Finland shows a structure centralized around a public research center, which is VTT. In the second model, a large number of actors take part developing different activities without being coordinated directly from an institution. In this case it is the actors own initiative the driving force for establishing collaboration relations through the projects undertaken. This model, with a higher degree of diversification in experimentation activities and a greater number of applications developed, corresponds to Sweden and Germany.

The knowledge accumulated by each of the four studied countries shows different characteristics. The greatest part of the knowledge comes directly from activities developed inside the country itself; making use of the experience acquired in previous used technologies, basically coal gasification and biomass combustion. Nevertheless, each of the countries has used this knowledge sources differently. It is important to emphasize the continuity in the development process as a key factor for the construction of a more solid knowledge base. This continuity has been boosted when the gas quality requirements, needed by gas utilization systems, have grown progressively.

The particular analysis of each country has allowed identifying several factors that influence the two mentioned functions. These factors have been analyzed together and classified according to its origin and its positive or negative influences. It is worth to mention the strong connection between each function. Thus, boosting one of them will influence positively the other and vice versa. In fact, a complete TIS analysis could show that an important number of the identified factors depend directly on the five remaining functions.

Knowledge development and diffusion is influenced by the unsatisfactory use of the obtained results in the research activities. The future expectations in this technology as well as the international collaboration among countries enhance the projects' performance. At the same time, the successful understanding among the involved actors, together with well defined trends, enhances the efficient use of the resources in the R&D activities. In that sense, a progressive development process, without any interruptions or changes, is also important. Finally, there are several external factors, difficult to be controlled, that affect directly in the development process; providing experience and discouraging further researches due to existing uncertainty.

Concerning entrepreneurial experimentation, some factors mean an important challenge for entrepreneurs' decisions. Firstly, it is important to mention the level of market competitiveness and feasibility when gasification projects are undertaken. Moreover, the economical situation is also an important factor to consider, due to the growing huge investments needed in new and more advanced projects. Even more, technology acceptation from plant owners and suppliers of complementary technologies, such as gas engines or boilers, will increase the number of technical resources available for those entrepreneurs trying to develop and commercialize gasification systems. The different organizational structures of the involved actors cause positive and negative influences that can affect not only the entrance of new actors but also the continuity of them. In contrast, political decisions also play an important role in entrepreneurial experimentation due to the sudden changes over the time which can create certain instability in demand and funding. Apart from that, technical thresholds concerning standardization and continuity of the technology are especially influential for encouraging further developments. Furthermore, the level of international cooperation and the possible alternatives in the foreign markets are other key factors affecting the performance of this function. Additionally, it is remarkable that entrepreneurs' confidence is strongly influenced by the technology and the reputation of actors involved in gasification. Finally, intensive efforts and willingness to develop new technologies, even as pioneers, are also determinant factors altering the related function.

In the economic analysis of the small scale CHP systems, the investment costs have turned out to be the biggest obstacle towards the commercial stage. The increase in process efficiency seems not to be enough in order to reach the prices offered by combustion technologies. It needs to come together with an increase of operational hours as well as the reduction of investment costs. The most optimistic predictions about the evolution of these factors, with learning rates of about 20%, foresee that competitive prices will be reached by 2012. However, after analyzing the technical evolution requirements of each prediction, it seems more sensible to think of learning rates of around 10%, which would allow reaching competitive prices by 2014. The same analysis was tried to be done for large scale IGCC facilities, but it could not be undertaken due to a lack of historical data about this type of plants. Expanding the database by including other countries which are experimenting on these kind of applications, like Denmark or US, could be one feasible solution.

Finally, it is important to point out that, during the collection of specific information about plants, it has been detected a disproportion among the data available from the different plants' scale. A lack of information about small scale commercial projects has been detected. There is evidence of their existence, but publications about their operability have not been found. Taking into consideration that there are some documents that underline the role of small scale projects, pushing BMG towards the commercialization stage, an efficient knowledge network is needed to encourage small entrepreneurs sharing know-how. Additionally, an organization in charge of coordinating small scale R&D activities would help to diffuse and organize the experience acquired in these kinds of projects. The inexistence of these connections among projects has caused failures to get left behind, forgetting the learning-by-failing process unfolded

In sum, the main conclusions of this thesis are:

- Two main motivations have moved actors to take part in BMG development. The increase of oil prices was the main driving force to attract new entrants during the 1970's and 1980's. The environmental constraints become the most important incentive since 1990's.
- While the intensity of research activities has increased significantly since the 1970's, the number of entrepreneurs aiming to implement the results has not grown sufficiently. Therefore, it is concluded that R&D resources are not being efficiently used.
- The great majority of plant failures and abandonment of planned projects are related to non-technical difficulties, such as economical issues, actors' uncertainty, modifications in the organizational structure of firms and changes in the demand.
- When there have emerged niche applications willing to integrate biomass gasification, a larger number of entrepreneurs have been motivated to undertake experiments. On the contrary, the entrance of new actors has been weakened mainly by difficulties when undertaking the initial investment costs.
- When requirements on gas quality have grown progressively pulled by the market demand, *Knowledge development and diffusion* has been influenced positively. By contrast, the inefficient use of R&D resources has weakened this function considerably.
- At large scale, the actors' interest has shifted from power production to fuel synthesis gas production. Only some actors in Austria and Finland still preserve some expectations on the potential of power applications via IGCC systems.

- At small scale, CHP applications have gained more attention over heating applications. However, there are fewer actors involved in small scale experimentation than in large scale.
- In spite of the progressive increase of funds, there is still a lack of incentives for building new plants, which is basic to make the technology competitive. Without building new plants, investment costs will not decrease and the needed operating experience will not be gathered.
- After assessing the feasibility of future scenarios for small scale CHP applications, it seems reasonable to think that biomass combustion prices can be reached by 2014. This would mean an electricity price reduction of 11% each time the installed capacity is doubled, which would correspond approximately to around 40 plants of 3MWth built within 6 years. This is only possible if incentives for the construction of new plants are properly given in the next years.

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APPENDIX A

Table A-1. Electricity prices and learning rates for the nine different future scenarios for 3MW$_{el}$ plants

	Scenario 1 (base)			Scenario 2 (50% eff. increase)			Scenario 3 (25% eff. increase)		
Year	2010	2015	2020	2010	2015	2020	2010	2015	2020
Electric eff. (%)	21,42	30,71	35,71	21,42	26,06	28,57	21,42	23,74	24,99
Gasifier eff. (%)	60,00	65,00	70,00	60,00	62,50	65,00	60,00	61,25	62,50
Power gen. Eff. (%)	35,70	47,25	51,01	35,70	41,70	43,95	35,70	38,76	39,99
Capacity factor (%)	85,00	85,00	85,00	85,00	85,00	85,00	85,00	85,00	85,00
Investment costs (€)	12 108 000	12 108 000	12 108 000	12 108 000	12 108 000	12 108 000	12 108 000	12 108 000	12 108 000
Price (€/kWh$_{el}$)	0,1183	0,1167	0,1160	0,1183	0,1174	0,1169	0,1183	0,1178	0,1175
b	-0,0123	learning rate	0,85%	-0,0075	learning rate	0,52%	-0,0043	learning rate	0,30%
	Scenario 4 (base + capital cost decrease)			Scenario 5 (50% capital cost decrease)			Scenario 6 (25% capital cost decrease)		
Year	2010	2015	2020	2010	2015	2020	2010	2015	2020
Electric eff. (%)	21,42	30,71	35,71	21,42	26,06	28,57	21,42	23,74	24,99
Gasifier eff. (%)	60,00	65,00	70,00	60,00	62,50	65,00	60,00	61,25	62,50
Power gen. Eff. (%)	35,70	47,25	51,01	35,70	41,70	43,95	35,70	38,76	39,99
Capacity factor (%)	85,00	85,00	85,00	85,00	85,00	85,00	85,00	85,00	85,00
Investment costs (€)	12 108 000	8 463 000	6 642 000	12 108 000	10 285 500	9 375 000	12 108 000	11 196 750	10 741 500
Price (€/kWh$_{el}$)	0,1183	0,0853	0,0688	0,1183	0,1017	0,0933	0,1183	0,1100	0,1057
b	-0,3043	learning rate	19,02%	-0,149	learning rate	9,81%	-0,0707	learning rate	4,78%
	Scenario 7 (base + capacity factor increase + capital cost decrease)			Scenario 8 (50% capacity factor increase)			Scenario 9 (25% capacity factor increase)		
Year	2010	2015	2020	2010	2015	2020	2010	2015	2020
Electric eff. (%)	21,42	30,71	35,71	21,42	26,06	28,57	21,42	23,74	24,99
Gasifier eff. (%)	60,00	65,00	70,00	60,00	62,50	65,00	60,00	61,25	62,50
Power gen. Eff. (%)	35,70	47,25	51,01	35,70	41,70	43,95	35,70	38,76	39,99
Capacity factor (%)	85,00	87,50	90,00	85,00	86,25	87,50	85,00	85,63	86,25
Investment costs (€)	12 108 000	8 463 000	6 642 000	12 108 000	10 285 500	9 375 000	12 108 000	11 196 750	10 741 500
Price (€/kWh$_{el}$)	0,1183	0,0830	0,0653	0,1183	0,1003	0,0908	0,1183	0,1092	0,1043
b	-0,373	learning rate	22,78%	-0,1661	learning rate	10,88%	-0,0791	learning rate	5,34%

Table A-2. Electricity prices for a small biomass combustion boiler (3 MW$_{el}$)

Year	2010 - 2015 - 2020
Electric efficiency (%)	23
Gasifier efficiency (%)	55
Power generation efficiency (%)	42
Capacity factor (%)	90
Investment cost (€)	11 250 000
Price (€/kWh$_{el}$)	0,1058

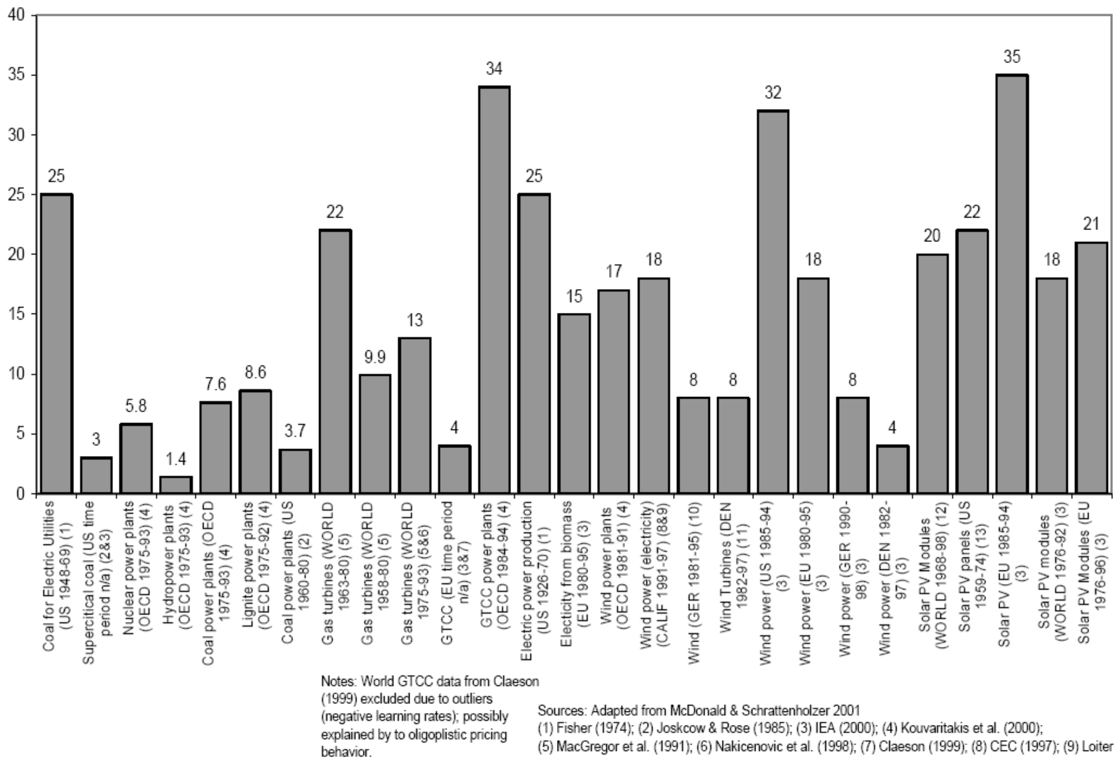

Figure A-1. Learning rates of different electricity generation technologies
Source: Köhler et al., 2006

Technology	**Present status**		**Target 2010 - 2015**		**Target 2015 - 2020**	
	Elect.Eff. %	Specif.Invest. €/kWe	Elect.Eff. %	Specif.Invest. €/kWe	Elect.Eff. %	Specif.Invest. €/kWe
Gasifier-engine (1-15 MWe)	20-30	3500-6000	30-35	2500-4000	35-40	2000-3000
Gasifier-MCFC (0.5-5 MWe)	na	(> 10 000)	35-40	< 10 000	45-50	2500-3000
Biomass IGCC (15-100 MWe)	35-40	3000-4500	40-45	2000-3500	45-50	1500-2000
Combustion and steam turbine	Elect.Eff. %	Specif.Invest. €/kWe				
1-5 MWe	17 - 25	3000-4000	only very limited development potential			
10-50 MWe	25 - 37	2000-3500	(mature technology, thermodynamic limitations)			

na = not available yet

Figure A-2. Targets for the gasification power plants.
Source: VTT (http://www.tut.fi/units/me/ener/IFRF/Liekkipaiva2006_EUProjectGasification_KURKELA.pdf)

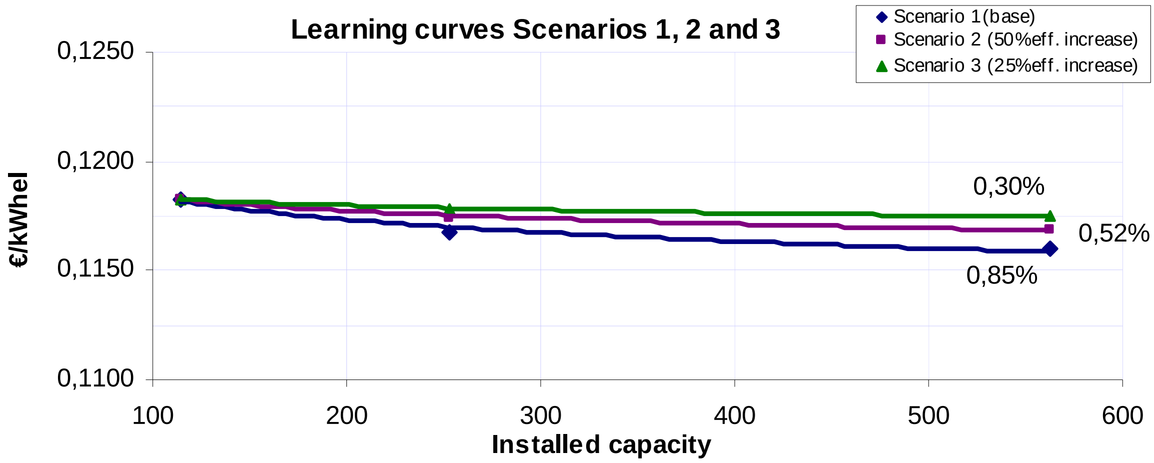

Figure A-3. Learning curves for Scenarios 1, 2 and 3.

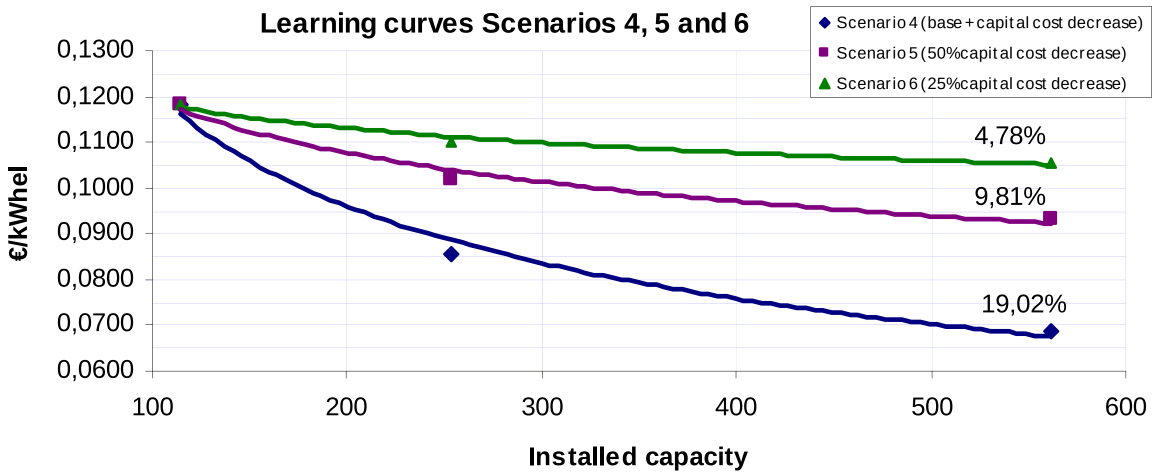

Figure A-4. Learning curves for Scenarios 4, 5 and 6.

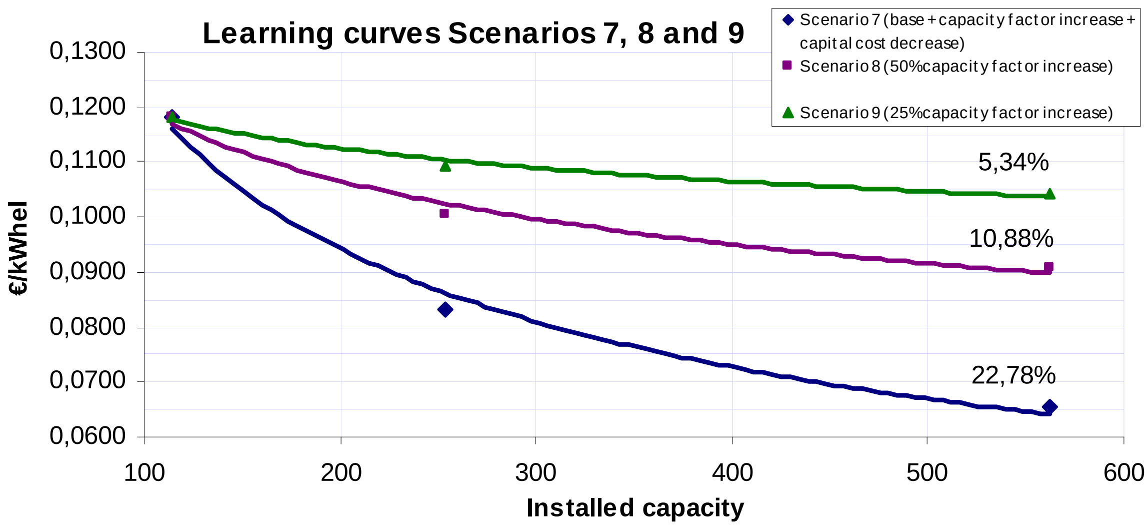

Figure A-5. Learning curves for Scenarios 7, 8 and 9.

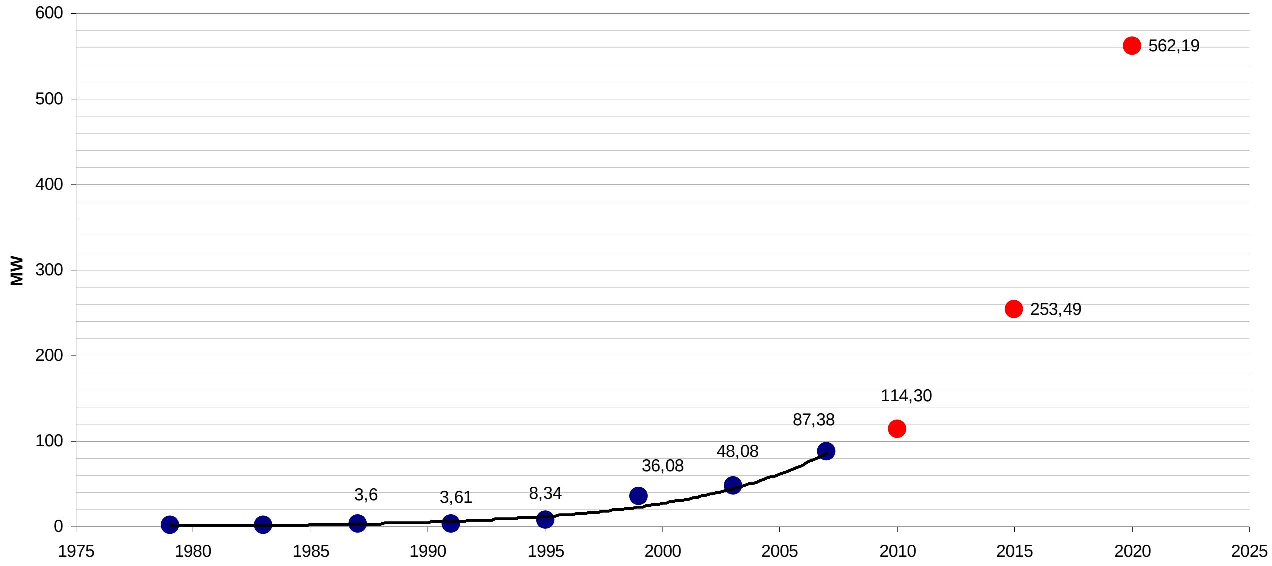

Figure A-6. Predicted installed capacity for gas engines

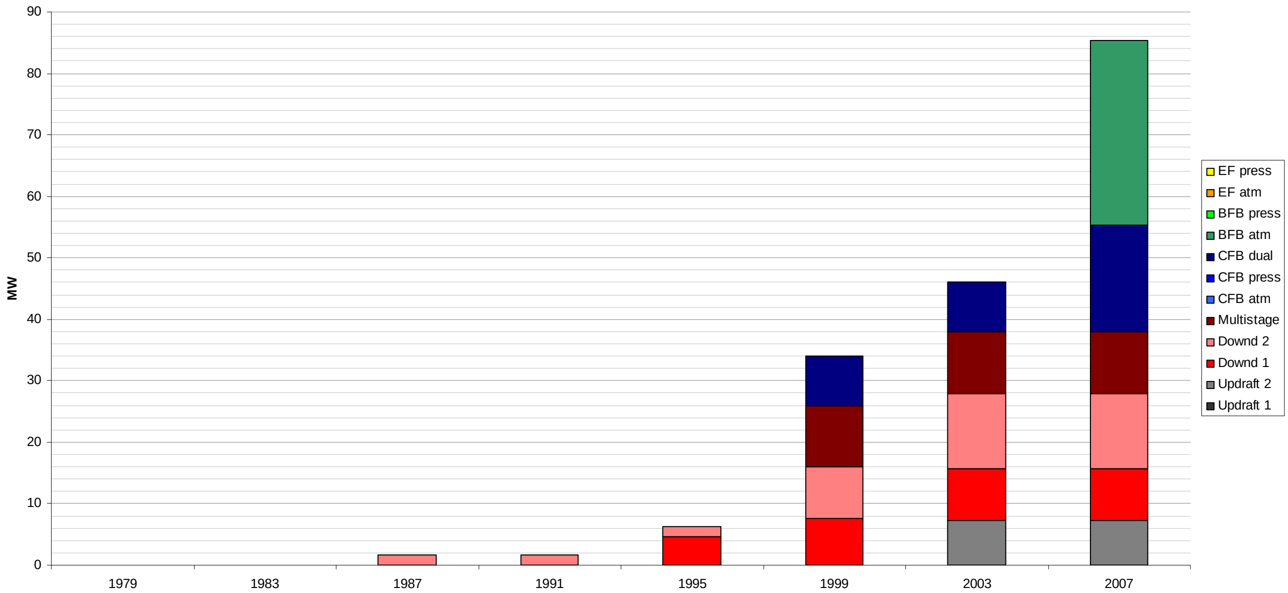

Figure A-7. Cumulative installed capacity for BMG plats with gas engine

APPENDIX B

Table B-1. Technologies for particle removal
Source: Knoef, 2005

Cleaning system	Subtypes	Associated technology	Main characteristics
Cyclones	-	CFB	❖ Effective and inexpensive ❖ Primary reduction of particles
Barrier filters	Cold gas filters	Small scale	❖ Anticorrosion
	Hot gas filters	Gas turbine	❖ Press. Gas – High separation efficiencies
Electrostatic precipitators	Wet	Small scale	❖ It can separate tars
	Dry		❖ Dust removed mechanically
Scrubbers	-	-	❖ Wet based separation tech.

Table B-2. Technologies for tar removal
Source: Knoef, 2005

Cleaning system	Subtypes	Associated technology	Main characteristics
Physical method	Scrubbers	-	❖ Collision with water ❖ Olga process
	Electrostatic precipitators (ESP)	-	Remove dust and tars at the same time
	Barrier filters	-	Tar accumulation on the filter surface
Thermal method	Thermal tar cracking	-	❖ Very high temperature ❖ No catalysts ❖ High economical and operational considerations
Catalytic method	In bed catalyst	Fluidized bed	High attrition of the bed material
		Fixed bed	Poor conversion due to low residence time and improper mixing

APPENDIX C

Table C-1. Technical problems identified in Swedish gasification systems for heating applications

Project	Problem	System part affected
Eisenmann	Problems like gas explosion and ash sintering in the reciprocating	Gas utilization system
Bioneer	Problems with feeding, varying gas quality, and high NOx emissions with fuel with high nitrogen content	Feeding system, Gas utilization, Emissions
Norrsundet mill	Gas leakages and explosions in the feed hopper Sintering problems in the gasifier	Feeding system Reactor
Värö mill	Erosion in the valves due to “hot dirty gas”. Expansion problems in the hot gas duct caused by settling of dust. Problems in the “hot gas” fired dryer related to the high dust content. The low BTU gas combustion characteristics “longer and cooler flame”. Tendency for char/tar adhesion to the surface of heat exchangers and pipes.	Gas utilization system
	A single hot gas cyclone was rather inefficient due to the large amount of dust produced by the CFB gasifiers	Reactor and Cleaning system

Table C-2. Technical problems identified in Swedish gasification systems for power applications

Project	Problem	System part affected
BIOFLOW/Värnamo	The use of limestone or dolomite as bed material caused deposits in the gas cooling system. Micro cracking in the ceramic filters Conversion of fuel bound nitrogen into NO_x	Gas cleaning system Gas cleaning system Emissions
TPS - Grève	Gas with high dust content	Gas utilization system
TPS - ARBRE	Mechanical problems associated with the movement of solids, including fuel and ash Limitations set by the gas cooler Mechanical problems with the fire tube heat exchanger that cools the gas leaving the tar cracker	Feeding system and reactor Gas cleaning system Gas cleaning system
Värnamo - WASTE	High sulphur emissions due to the use of RDF as feedstock	Emissions
TPS - ARBRE	Very complicated cleaning process and under-dimensioned gas cooling system	Cleaning process
Chemrec - Frövi	Problems with the refractory lining of the EF gasifier	Reactor
Chemrec - New Bern	Problems with the refractory lining of the EF gasifier	Reactor

Table C-3. Non-technical problems identified in Swedish gasification systems

Project	Problem	Reason
Värö mill	Low oil price	Competing fuel prices
TPS motor fuels at Värnamo	Lack of public support. I was considered too risky to be borne by private companies.	Lack of support
Värnamo TPS – Grève	Low electricity price Limited RDF fuel supply	Competing fuel prices Feedstock supply
TPS - ARBRE	Departure of the plant constructor from the project due to bankrupt Inadequate documentation and co-ordination between sub-contractors Insufficient dedicated managerial personal due to changes in the strategy of project managers firms.	Other reasons Coordination Project failed and was placed in liquidation
Vattenfall IGCC plant concept	High capital costs and low electric price	Competing fuel prices
Brazilian BIGCC	Company policies and perspectives changed	Motivation

Table C-4. European Research projects in which Sweden is involved.

Project	Aim	National Firms involved	Other countries involved	Funding from
ARBRE (1993 - /)	Demonstrate the potential of coppice as fuel BIGCC	TPS	UK, Germany, France, and Sweden	EC (11 M€)
Brazilian BIG-GT (1992 - /)	Confirm the commercial viability of BIGCC	TPS	Sweden, Brazil	UNDP, STEM and EC
Värnamo Demo programme (1996-2000)	Demonstrate the performance of pressurized BIGCC, verify its status and future potential.	Sydkraft AB	Sweden, France	Elforsk AB, STEM, EC.
Synthesis gas production in Värnamo. (2001 - /)	Study de possibilities of developing biomass-based motor fuel DME.	TPS, Volvo, LRF, Växjö municipality	Sweden	-
Värnamo WASTE (2004-2006)	Demonstrate IGCC operation on RDF.	VVBGC, Sydkraft AB	Sweden, Greece	EU
CHRISGAS (2004-2009)	Development of a process to produce clean hydrogen-rich synthesis gas	Växjö University, TPS, KTH, VVBGC, SEP Scandinavian project, KS Ducente, Växjö Energi.	Sweden, Denmark, Finland, Germany, Italy, Netherlands, Spain	EU, STEM, other team members.
Part of the EU RENEW project – (2004 – 2007)	Development of a BLG process	Sweden BLG R&D Centre, Chemrec AB, STFI, Volvo, Lunds Universitet	Sweden, (Austria, Germany, Spain, Greece)	EU, pulp and paper industries STEM, Vattenfall AB
BLGMF and BLGMF II (2002 – 2003 / 2005 -)	Study the feasibility to produce methanol, DME and F-T as transport fuels based on BLG	Nycomb Synergetics, STFI Packforsk, Structor Húlthen & Stråth, Statoil Lubricants, KTH	Sweden	EU Alterner II programme (400000€) /
NOVACELL	Establish a sustainable sulphur free pulping process.	STFI, Chemrec, KIRAM, ÅF–Celpap, Stora Enso, Kappa Kraftliner.	Sweden, France, Germany, Slovakia, Austria	EU
BAL – Fuels & BioMeeT & BioMeeT II (1997 - 2003)	Realisation of a concrete plant for production of motor fuels (methanol/DME), fuel gas, CHP from BMG	Trollhättan Municipality, Trollhättan Energy, Saab Automobile, Volvo, Vattenfall, Trollhättan.	Sweden, UK, Belgium	EU, STEM

Table C-5. European research projects in which Finland has been involved.

Network/global project	Aim	National firms involved	Countries involved	Funding from
Shredder residue (1998)	Gas cleaning	Foster Wheeler and others	FI, BE, SE	Tekes
EU/Lahti STREAMS	Feeding system	Foster Wheeler and others	FI, DK, DE, PT	EC, M€ 8.7
Novel gasifier (1999)	Gasifier	Foster Wheeler and Condens Oy	FI	Tekes
STRAWGAS (2000-2001)	Process and gasifier	Foster Wheeler	FI	EC
Gasification plant in Varkaus (2001)	Process	Foster Wheeler. Then, Corenso Oy [plant owner]	FI	Tekes
GASASH (2002)	Optimisation	Foster Wheeler and others.	FI, NL, ES, UK.	EC
COMBIO Project (2003-2006)	Liquid fuels for heating	Neste oil, Fortum Oil, Vapo Oy, VTT	FI, IT	EC
UCG project (2004)	Cleaning system	Foster Wheeler, Vapo Oy and others.	FI	Tekes
NoE BIOENERGY (2004)	Bioenergy chain	NoE is a partnership of eight leading institutes in Bioenergy	FI, SE, FR, UK, DE, AT, NL, PL	FIN&EU, M€ 8
BIGPOWER (2005)	Gasifier	Condens Oy, Carbona Oy, Repotec, Güssing and other some R&D organisations	AT, DE, GR, UK, LT	EC, M€ 1.7

Table C-6. Technical problems identified in German gasification systems

Project	Problem	Consequence
Eckernförde	Guaranteed installed power could not be reached. No continuous operation was possible	Abandonment of the project
Espenhain	Guaranteed power could not be reached. Running at 50% of the expected load.	Project failure
	Technological shortcomings in gas quality, low heating value and instability of the process.	
Siebelehn	Low overall efficiency due to the low efficiency of the gas-gas heat exchanger	Plant shut down two years after the commissioning.
Boizenburg	High tar content, low and poor char quality, high water vapour in the gas, low gas quality	Project mothballed one year after the commissioning
Pöls	No continuous operation due to the contamination of the lime with the ash contained in the fuel gas.	Stopped commercial operation. Now used for testing and evaluation purposes only.

Table C-7. Non-technical problems identified in German gasification systems

Company/Project	Problem	Consequence
Oxygen blown melting process development by Ingitec	Insolvency and bankrupt of the technology users.	Technology developed still to be proven
SVZ Schwarze Pumpe plant	Insolvency of the plant owner.	2 years interruption of the operation
Lurgi	Inadequate market pull and other related considerations	Lurgi has halted its BMG marketing efforts
Campus Espenhain power plant (supplied by HTV)	Technology supplier came into financial difficulties and went bankrupt	Project failure
Siebelehn (supplied by PPS)	High biomass fuel price.	Plant shut down 2 years after the commissioning.

Table C-8. European Research projects in which Germany has been involved.

Project	Orientation	German suppliers and researchers involved	Countries involved
Coordinated by German actors			
AERGAS II	Development of low-cost small gasification process.	ZSW (coord.), University of Stuttgart	DE, AT, GR, CH, CY, NO
RENEW	Production of motor vehicle biofuels	Volkswagen AG (coord.), ZSW, CUTEC, UET, IE GmbH	DE, AT, SE, PL, FR, IE, ES, GR, CH
BIOCELLUS	Study of the performance of fuel cells with biogas.	TU Munich (coord.), Stuttgart University, D.M.2	DE, AT, DK, NL, GR, NO, SI
ISCC	Production of hydrogen rich producer gas.	University of Stuttgart (coord.), ZSW, Brandenburg UT.	DE, AT, FI, GR, PL, UK, ES
WINEGAS	Production of hydrogen rich producer gas.	Bauer Kompost GmbH (coord.), ZSW	DE, NL, IE
AREHCC	Development of low-cost small gasification process feed with sludge.	Philips Semiconductors GmbH (coord.), Bremen University, Duisburg-Essen University	DE, FR, BE
BIOHPR	Development of a concept for the production of hydrogen rich producer gas.	TU of Munich (coord.), Stuttgart University, Zentrale kraftwerkstechnik	DE, AT, GR, RO, CY, HU
Coordinated by other European countries			
GREENSYNGAS	Development of gas cleanup system for the production of vehicle fuels	TU Munich, RC Juelich	DE, SE, IT, NL, NO, UK
CHRISGAS	Development of a method to produce hydrogen-rich gases.	RC Juelich	DE, SE, NL, IT, DK
ADEG	Development of decentralized systems in the area of Western Balkans based.	Stuttgart University	DE, GR
DE-TAR	Evaluation of supercritical wet oxidation/gasification for liquid waste.	Federal Research Centre for forestry and forest products	DE, DK, IT
MICROCHEAP	Integration of Micro-CHP and Renewable Energy Systems.	German Society for sun energy EV, Fraunhofer Society EV, Institute of solar energy	DE, UK
AER-GAS	Development of a new method for the production of a hydrogen-rich gas.	IVE Weimer, Stuttgart University	DE, AT, CH, CY
TARGET	Study of the influence of tar on fouling, emission and efficiency of micro and small scale gas turbines	Stuttgart University	DE, SE, UK, CH, NL
SUPERHYDROGEN	supercritical water gasification for the production of renewable hydrogen	UHDE High Technology	DE, NL, UK

Table C-9. European Research projects in which Austria has been involved

Network/global project	Orientation	Firms involved in Austria	Countries involved	Funding from
BioCoComb (1997-2001)	Co-fired power station	TU Graz	AT, IT, IE, DE, BE	EC-THERMIE program
AER-GAS (2002-2004)	Reforming – Hydrogen Rich gas	TU Vienna	CY, DE, AT, CH	EC
CleanStGas gasifier (2004)	Fixed bed-Staged	TU Graz	-	-
Biocellus (2004-2007)	fuel cell utility system	TU Graz	DK, NL, DE, GR, AT, NO, SI	EC= M€ 2.5
RENEW (2004-2007)	Advance power trains	TU Vienna, Repotec, Kraftwerk Güssing	AT, SE, DE, PL, FR, IE, ES, GR, CHE	EC= M€ 8.23
CLEAN-E (2005-2006)	Clean energy from biomass	TU Vienna	SE, UK, IT, FR, NL	EC
BIGPOWER (2005-2008)	High efficiency power	TU Vienna, Repotec, Kraftwerk Güssing	FI, AT, GR, DE, UK, LT, UK	EC, M€ 1.7
AER-GAS II (2006-2008)	Fluidized bed gasification with in situ hot gas cleaning	TU Vienna, GE Jenbacher	AT, GR, DE, CH, CY, NO	EC= M€ 1.8
BIOSNG (2007-2009)	synthetic natural gas (SNG) - methanation	TU Vienna, Repotec, CTU	AT, CH	EC