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The emergence and troubled growth of a ’bio power’ innovation system in Sweden*

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Abstract

Bio power, i.e. production of power (and heat) using biomass, has a tremendous potential to deliver CO_2 neutral energy in the Nordic countries. This paper analyses the evolution of a bio power innovation system in Sweden where particular attention is given to driving forces and obstacles to a large scale diffusion of bio power. In the 1980s and 1990s, this innovation system went through a successful ‘formative phase’ in which all the constituent components of the ‘infant’ system were put in place. With the introduction of green certificates and emission trading rights, incentives were created that were large enough to shift the system into a ‘growth phase’, where the extensive district heating system and voluminous production in the paper and pulp industry can be used to produce power on a large scale. An investment boom is now underway and output of bio power is rapidly growing. Yet, there are still substantial obstacles to a realisation of the full potential of bio power. Four of these are outlined and an associated set of policy challenges are specified.

Key words: biopower, Sweden, innovation system

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Introduction

The dominance of fossil fuel in the world energy system is associated with clear environmental and climate challenges. A wider use of renewable energy technology is seen as one way of meeting these challenges. For instance, the European Union aims at increasing the share of renewable energy of the supply of electricity from about 14 per cent in 1997 to 21 per cent by 2010 (Commission of the European Communities, 2005). To obtain, and go beyond this share, a range of renewable energy technologies need to be diffused. Whereas wind and solar power are diffusing rapidly in some countries, the European Union has recently pointed to a poor realisation of the potential of biomass electricity (Commission of the European Communities, 2005).

Since the early 1970s, biomass has greatly expanded its share in the Swedish energy system in a process that has been labelled a ‘quiet revolution’ (Kåberger, 2002). This growth has not ceased and biomass accounted for 110 TWh of the Swedish energy supply in 2004 – up from 48 TWh in 1980 (Energimyndigheten, 2005, table 9). Yet, until very recently, nearly all of the energy was used in the form of heat only. A large potential for expanding the supply of ‘bio power’ was, thus, built up. This was noted by the Commission (2005, p. 35), which pointed to Sweden as lagging behind Finland and Denmark in realizing its potential.

Yet, through a set of government initiatives, a bio power innovation system went through a successful ‘formative phase’ in the 1980s and 1990’s.[1] All the constituent components of an ‘infant’ system were then put in place in terms of conventional bio power (steam cycle) and experiments were undertaken with gasified biomass - the next generation of technology with a larger potential for power generation.

With the introduction of tradable green certificates in May 2003 and, in 2005, emission trading rights, incentives were put in place to enable the system to shift from a formative phase to a ‘growth phase’ where the inherently large potential can begin to be reaped. This potential is, however, not automatically realized with the new incentives as competing technologies (in

[1] This refers to combined heat and power.

particular fossil gas)[2] are advancing their position; the uncertainty facing investors is high and the eventual shift to gasified biomass remains very uncertain indeed. Moreover, the costs associated with green certificates have turned out to be very high which means that there may well be a back-lash as and when the order of magnitude of the costs are realised.

The purpose of this paper is to analyse the evolution of this ‘bio power’ innovation system and to specify the key policy challenges for realising the large potential of bio power in Sweden. The paper is structured as follows. Section 2 contains a description of the technology and the technical context in which it is situated. The analytical framework is outlined in section 3 whereas section 4 focus on the empirical analysis of the evolution of the innovation system. Section 5 identifies four policy challenges and the final section contains some concluding remarks.

2. Biomass combined heat and power - the technology and its diffusion

Conventional combined heat and power generation involves burning fuel and passing steam through a steam turbine (steam cycle). The remaining heat is then used in either a district heating system or for industrial purposes in the form of process steam. In a more advanced variant, a gas is used as fuel and the gas passes first through a gas turbine. The still hot gas is then used to heat water which generates steam, as in the steam cycle. The benefit with this more advanced version is that the power-to-heat ratio may be substantially increased compared to that in the steam cycle (SOU 1995:139; Energimyndigheten, 2005).[3]

The potential diffusion of biomass CHP (conventional or combined gas and steam cycle) is, of course, closely related to the volume of district heating and to the size of the relevant industrial activities, largely the size of the paper and pulp industry (SOU 2001: 77; Energimyndigheten, 2005).

[2] Waste is increasingly used as fuel and it encroaches on the market for bio power. As the power to heat ratio is lower from waste, this reduces the potential production of bio power. For reasons of space, we will not , however, deal with this issue.
[3] The alfa value (the relationship between power and heat generated) is said to be 0.5 for conventional steam cycle (at most) and at most 1.3 for gasified biomass (SOU: 1995:139, page 202). Energimyndigheten (2005, page 45) suggests that the alfa value is 1.1.

The district heating system is not only large but it grew from 34.5 TWh in 1980 to 53.5 TWh in 2004 (Energimyndigheten, 2005, table 26). A particularly notable development is its growing use of biomass. In 2004, as much as 31.3 TWh[4] was used in that application – up from 2.3 TWh in 1980 (ibid, table 36). In addition, industry used nearly 52 TWh of biofuel in 2004, up from 35 TWh in 1980 (ibid, table 12 and 15).[5] The use of biofuel for electricity production was, however, very modest until very recently. In district heating, the use of biofuel for that purpose amounted to 1 TWh in 1995. It began to rise in 2003 and 2004 only, after the introduction of tradeable green certificates, see more below. In industry, the use of biofuel has been less modest (2.4 TWh in 1995) and also here it rose in 2004 (ibid, tables 35 and 36). Hence, compared to the very sizeable use of biomass in district heating and in industry, the level of biopower production has been of marginal nature, suggesting an underused potential.

The potential of bio power has been subject of a number of studies (e.g. SOU 1991:93; Knutsson and Werner, 2002; Elforsk, 2003; SOU 2005:33) and the figures mentioned vary a great deal. Some have a relatively short term focus and they stress, therefore, a number of obvious limiting factors. Among these, we can note supply restrictions in the equipment industry and weak economic incentives to replace relatively new hot water boilers in district heating systems.

If we, however, take a longer term view, the potential is larger. Knutson and Werner (2002) suggest that the longer term potential of biopower in district heating may be 12 TWh.[6] Elforsk (2005), however, argues that by 2015, output may be about 15 TWh in district heating systems and most it would be biopower. [7] SOU (2005:33, p. 139) suggests that the potential in industry (presumably given the size of the paper and pulp industry) may be 10-15 TWh. Taken jointly, this implies a potential of 22-30 TWh. To this, we may add a number of factors that may enlarge this potential further.

[4] To this can be added 7.2 TWh of waste.
[5] Most of this is used in the paper and pulp industry (Energimyndigheten, 2005, table 35).
[6] This assumes that the district heating system does not grow any more.
[7] A recent study suggests that the potential in 2015 would be about 13 TWh in district heating systems and in industry (Energimyndigheten, 2005)

- A continued growth in district heating. District heating has grown over many years and Svensk Fjärrvärme (2004) argues that the potential is far from reached. Indeed, the present volume of a bit more than 50 TWh may be raised significantly, even towards 80 TWh (Svensk Fjärrvärme, 2004). There are at least three ways whereby the power potential may be increased. The first is to enlarge and make denser the existing district heating systems. The second is to connect the growing number of smaller district heating systems to the main grid (Ahnland, 2004; Svensk Fjärrvärme, 2004, Peters, 2005). A third is to connect some of the currently 550 existing independent systems which will open for a larger production of power (Ahnland, 2003; Bengtsson, 2003; Peters, 2005).
- Three features of technical change in power production may influence the potential. The first is a reduction in scale sensitivity for bio power by modularisation of smaller scale installations – a process developed by Wärtsilä (Johnson, 2005). The second is a development towards higher steam pressures which allows for a higher power output (Modig, 2005). The third is gasification of biomass which has the potential to radically increase the alfa value (the ratio between power and heat). Whereas conventional steam cycles may have a ratio of 0.5, gasification may raise this to the double (Energimyndigheten, 2005).

In sum, the potential for CHP production has over the years increased greatly and a growing part of that potential refers to biomass CHP production. This potential is, furthermore, not constant but appears to be continuously enlarged.[8]

Yet, there are many substitutes to biomass CHP. In the Swedish context, nuclear power has constituted the prime substitute. After a massive build-up of nuclear capacity in the 1980s, the price of power has been very low (Kåberger, 2002).[9] It is only recently that prices have reached a level where new investments have been considered. Another, and emerging, substitute for bio power is fossil gas. The pipeline was originally limited to the southwest coast and has only recently started to be extended. Yet, there are plans to build pipelines across Sweden and include the most populated parts. A third substitute is that of gasified coal. Much work is directed towards this technology in USA (Olofsson, 2005) and it may well become a strong substitute to gasified biomass in the future.

[8] For instance, Borås Energy's current production is 122 GWh. This may increase, within 5-10 years to 250 as a consequence of a) investment in a new turbine and b) enlarging the net e.g. via connecting the main grid to peripheral ones. Gasified biomass would enlarge the potential further (Peters, 2005).

[9] Indeed, CHP production, using all types of fuel, has been quite modest, in fact very underdeveloped (SOU 2005:33). Production of power amounted to 5.6 TWh in 1980. An expansion of nuclear power then led to a reduction in CHP production and it was not until 1994 that the same level was reached. By 2004, the supply had grown to 7.5 TWh (Energimyndigheten, 2005, table 18 and 22). Hence, CHP production has remained broadly the same since 1980 while its potential increased greatly.

3. The analytical framework – structure and dynamics of innovation systems

The analytical framework used to study the development of biopower in Sweden is that of an emerging technological innovation system (TIS). This section will outline the framework used. It consists of three parts. The first section deals with the constituent components of such a system and how they emerge. The second focus on what the system achieves in terms of seven functions whereas the third outlines how we can we can explain what is achieved in terms of a set of inducement and blocking mechanisms.

3.1 Structural change

A technological innovation system (TIS) may be defined as (Carlsson and Stankiewicz 1991, p. 111):

> “.... network(s) of agents interacting in a specific technology area under a particular institutional infrastructure to generate, diffuse, and utilize technology.“

It is, thus, made up of three elements: firms and other organisations, networks and institutions.[10] The *firms* are found within the whole value chain. For instance, in the case of solar cells they include manufacturing of machinery to make thin film solar cells, machinery suppliers to wafer producers, cell and wafer producers, engineering firms designing and delivering whole systems, roof and façade manufacturers, electricians, architects etc. Other organisations include: universities and other parts of the educational subsystem, industry and other professional organizations, bridging organizations, other interest organizations, such as Greenpeace, and government bodies.

In the course of the formation of the TIS, each new firm that enters the system brings knowledge, capital and other resources into the industry. New entrants experiment with new combinations, fill ‘gaps’ (e.g. become a specialist supplier) or meet novel demands (e.g. develop new applications). A division of labour is formed and further knowledge formation is stimulated by specialisation and accumulated experience (e.g. Smith, 1776; Rosenberg, 1976). Similarly, other

[10] Artefacts may be argued to be an additional structural component (Sandén and Jonasson, 2005).

organisations enter into the system and enriches it, for instance in the form of Universities providing specialised courses; bridging organisations that act as meeting places and interest organisations that promote the technology in the public arena.

The *networks* can be of various types. A first set of networks is learning networks. These can be user-supplier networks, networks between related firms (Porter 1998), networks between competitors (direct or via a joint labour market) or university-industry networks. These constitute important modes for the transfer of tacit and explicit knowledge. The network also influences the perception of what is possible and desirable, i.e. images or expectations of the future, which guides specific investment decisions (Carlson and Jacobsson, 1993; Geels and Raven, 2006).

A second type of network refers to those that have as objective to influence the political agenda. These are focussed on in the political science literature (see, e.g., Sabatier, (1998); Smith, (2000); Rao, (2004) and Suchman, (1995)), which argues that policy making takes place in a context where *advocacy coalitions,* made up of a range of actors sharing a set of beliefs, compete in influencing policy in line with those beliefs (Smith, 2000). The political science literature looks at coalitions in a non-technology specific manner, which is reasonable considering that the political debate over, say, climate change, is not necessarily focused on specific TIS. However, for a new technology to gain ground, *technology specific coalitions* need to be formed and to engage themselves in wider political debate.

As firms and other organisations enter into the TIS, these two different types of networks have to be formed, enlarging the resource base of the individual firm (in terms of information, knowledge, technology etc.) and giving the collective a voice in the political arena.

The third element is institutions. These refer to legal and regulatory aspects as well as to norms and culture. In this, institutions regulate interactions between actors (Edquist and Johnson, 1997) and define the value base of various segments in society (norms). Institutions also refer to beliefs (cognition) that influence firms' decision in the form of frames (Geels and Raven, 2006) that structure learning processes (problem agendas, guiding principles, ways to do business, etc).

Institutional change (and by implication its politics) is at the heart of the process whereby new technologies gain ground (Freeman and Louca, 2002). Institutional alignment may involve a redirection of science and technology policy in order to generate a range of competing designs. This knowledge creation may have to begin well in advance of the emergence of markets, but it also needs to be sustained throughout the evolution of the system. Institutional alignment is, however, also about market regulations, tax policies, value systems, beliefs etc. that may be 'closer' to the operation of specific firms.

The centrality of institutional alignment implies that firms in competing TIS not only compete in the market for goods and services but also to gain influence over institutions. As Van de Ven and Garud (1989, p. 210) put it,

> "…firms compete not only in the marketplace, but also in this political institutional context. Rival firms often cooperate to collectively manipulate the institutional environment to legitimize and gain access to resources necessary for collective survival…."

The formation of a new TIS, thus, involves three structural processes; entry of firms and other organisations, formation of networks and institutional alignment. In order for the TIS to eventually have an impact of the energy sector, these three constitutive elements need to be put in place. This is achieved in a formative phase (Jacobsson and Bergek, 2004). The literature characterizes this phase in three ways. First, there is a high uncertainty facing investors and policy makers in terms of technologies, markets and regulations (Afuah and Utterback, 1997; Klepper, 1997; Kemp et al., 1998). Second, it lasts for decades. Breshanan et al. (2001, pp 843-844) summarize the lessons from a set of case studies on the evolution of ICT clusters as follows:

> "Another similarity … is the degree of investment, effort and building needed to set up the background for an innovation cluster's take off. …it takes years of firm-building and market-building efforts… sometimes these long-term investments in national or regional capabilities can grow for a long time in what seems like a low-return mode before the take off into cluster growth…"

Third, putting the constitutive elements in place is a cumulative process of many small changes. Van de Ven and Garud (1989, p. 203) and de Fontenay and Carmel (2001 p. 26) appropriately describe the formative stage as one where accumulation of many small changes begins to form a new entity, industry or TIS.

Once the elements are put in place, the TIS is in a position to shift to a growth phase (Carlsson and Jacobsson, 1997; Porter, 1998) and begin to have an impact on the energy system. Any change in a component in the system, e.g., a new entrant or a change in the institutional set-up, may trigger a set of actions and reactions that propel the system forward. The boundaries, in terms of both actors and knowledge, may consequently alter, sometimes quite rapidly (Carlsson et al., 2002).

As it does so, a chain reaction of powerful positive feedbacks may materialize, involving many (or all) of the constituent components of the TIS.[11] The linkages between these may, thus, turn out to be circular, setting in motion a process of cumulative causation (Myrdal, 1957). Indeed, these virtuous circles are central to a development process – as they are formed, the evolution of the TIS becomes increasingly self-sustained.

Tracing the evolution and interdependencies of the structural elements as they are "put in place" in a given TIS is, of course, doable. Yet, whereas we know that these structural elements need to be built up, we can't assess the 'goodness' of a particular structure more than by relating it to a final outcome, such as the installed stock of wind turbines. Explaining the causal mechanisms between structure and performance is, however, beyond us without introducing intermediate variables. If the purpose of a study is 'simply' doing a historical analysis, a systematic analysis of such variables may be unnecessary. However, if the objective is to inform policy makers of what needs to be done to, say, speed up the rate of diffusion of biomass CHP, then we need to systematically analyse a set of intermediate variables between structure and the final performance. Having done that, we will be able to explain the current (possibly slow) rate of diffusion and advice policy makers of weaknesses in the TIS.

3.2 Functional analysis

We suggest that this is done by introducing a second level of key processes in industrial development which addresses directly what is being achieved in the TIS – bridging the gap between structure and performance. These key processes are here referred to as "functions of innovation systems" (Johnson, 1998; Jacobsson and Johnson, 2000, Hekkert et al., 2006). The main advantage of a functional analysis is that we can separate structure from content and focus

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[11] For instance, new entrants may be induced by market opportunities and generate positive externalities (e.g. a thick labour market) that reduce entry costs for further entrants (Porter, 1998); networks may become more dense; institutions may continue to be reshaped to suit the evolving needs of the new system and universities may expand their research and education in the relevant knowledge fields (Porter, 1998).

on what is being achieved in the TIS in terms of a set of key processes that have a direct influence on the performance of the system. In what follows, we will outline seven functions.[12]

(i) Knowledge development and diffusion

This is the function that is normally placed at the heart of a TIS in that it is concerned with how the TIS performs in terms of its knowledge base and, of course, its evolution. The function captures the breadth and depth of the knowledge base of the TIS and how that knowledge is diffused and combined in the system.

(ii) Influence on the direction of search

If a TIS is to develop, a whole range of firms and other organizations have to enter into it. These do not only have to have the ability to identify new opportunities but there must also be sufficient incentives and/or pressures for them to undertake investments in the TIS. The second function is the combined strength of factors influencing the search and investment behaviour.[13] Examples of these are beliefs in growth potentials (van Lente, 1993; Raven, 2005), regulations, articulation of demand by leading customers (e.g. von Hipple, 1988) and technical bottlenecks (e.g. Rosenberg, 1976).

(iii) Entrepreneurial experimentation

A TIS will evolve only if there are entrepreneurs that conducts technical experiments, delving into uncertain applications and markets, discovering and creating opportunities. Handling these uncertainties is a fundamental feature of technological and industrial development. From a social perspective, the way to do so is to ensure that many entrepreneurial experiments take place. These experiments imply a continuous probing into new technologies and applications, where many will fail but some may succeed. As emphasised in Strategic Niche Management (e.g. Raven, 2005; Geels and Raven, 2006) a multi-dimensional social learning process will unfold through the course of these experiments. Of course, in this learning process, knowledge

[12] These build on Bergek et al., (2005).
[13] This function also covers the mechanisms influencing the direction of search *within* the TIS, in terms of different competing technologies, applications, markets, business models etc.

formation takes place, but of a more applied nature than that captured under the first functional heading.[14]

(iv) Market formation

For an emerging TIS, markets may not exist, or be greatly underdeveloped. Market places may be absent, potential customers may not have articulated their demand, or have the competence to do so, price/performance of the new technology may be poor, uncertainties may prevail in many dimensions. Institutional change, e.g. the formation of standards, is often a prerequisite for markets to evolve as are the availability of complementary products and services.

Market formation normally goes through three phases with quite distinct features. In the very early phase, ‘nursing markets’ need to evolve so that a ‘learning space’ is opened up (Ericsson and Maitland, 1986, Kemp et al., 1998), in which the TIS can find a place to be formed. The size of the market is often very limited. This nursing market may give way to ‘bridging’ markets which allow for volumes to increase and for an enlargement of the TIS in terms of number of actors (Andersson and Jacobsson, 2000). Finally, in successful TIS, mass markets may evolve, often several decades after the formation of the first market.

(v) Legitimation

Legitimacy is a matter of social acceptance and compliance with relevant institutions; the new technology and its proponents need to be considered appropriate and desirable by relevant actors in order for resources to be mobilized, for demand to form and for actors in the new TIS to acquire political strength. Legitimacy also influences expectations among managers and, by implication, their strategy (and, thus, the function ‘influence on the direction of search’). As is widely acknowledged in organization theory, legitimacy is a prerequisite for the formation of new industries (Rao, 2004) and, we would add, new TIS. Legitimacy is not given, however, but is formed through conscious actions by various organisations and individuals in a process of legitimation, which eventually may help the new TIS to overcome its ‘liability of newness’ (Zimmerman and Zeitz, 2002).

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[14] One particularly important form of learning is that related to institutional constraints to the growth of the system – constraints that are ‘discovered’ as and when entrepreneurial experimentation takes place.

This process is uncertain, may take considerable time and is often complicated by competition from adversaries defending existing TISs and the institutional frameworks associated with them (Van de Ven and Garud, 1989). Hence, the formation of "political networks" sharing a certain vision and the objective of shaping the institutional set-up forms a key feature of the process of structural change influencing this function.

(vi) Resource mobilization

As a TIS evolves, a range of different resources needs to be mobilized. These resources are of different types, technical, scientific, financial, etc. Hence, we need to understand the extent to which the TIS is able to mobilize human capital, financial capital and complementary assets.

(vii) Development of positive externalities

As markets go beyond the first niches, there is an enlarged space in which the emerging system can evolve and the functions be strengthened. Structural change in the form of entry of firms is central to this process. First, new entrants may resolve at least some of the initial uncertainties with respect to technologies and markets (Lieberman and Montgomery, 1988), thereby strengthening the functions 'influence of the direction of search' and 'market formation'. Second, new entrants may, by their very entry, legitimate the new TIS (Carroll, 1997). New entrants may also strengthen the 'political' power of advocacy coalitions that, in turn, enhances the opportunities for a successful legitimation process.

By resolving uncertainties and improving legitimacy, new entrants may confer positive externalities on other firms, established as well as new entrants. Further externalities may arise due to the co-location of firms. Marshall (1920) discussed economies that were external to firms but internal to a location. Developing his ideas, Audretsch and Feldman (1994) and Krugman (1991) outlined three sources of such economies:[15]

- Emergence of pooled labour markets, which strengthens the function 'knowledge development and diffusion' in that subsequent entrants can recruit staff from early entrants (and vice versa as times go by).

[15] In addition to these, they also mention provision of non-tradable inputs specific to an industry.

- Emergence of specialized intermediate goods and service providers; as a division of labour unfolds, costs are reduced and further ‘knowledge development and diffusion’ is stimulated by specialization and accumulated experience.
- Information flows and knowledge ‘spill-overs’, contributing to the function ‘knowledge development and diffusion’.

Hence, new entrants may contribute to a process whereby other functions are strengthened, benefiting other members of the TIS through the generation of positive externalities. This function is therefore not independent, but rather one which indicates the dynamics of the system in the sense that the functions grow in strength.

3.3 Internal versus external forces of change in structure and functions

Each technology-specific TIS has unique features in terms of the constellation of actors, character of networks and nature of institutions that influence the strength of the functions. The system evolves, in part, as a result of the internal dynamics of the TIS bringing about changes in both structure and functions. As noted by Myrdal (1957), in a rapidly developing system, a chain reaction of positive feedback loops may materialise setting in motion a process of cumulative causation. Hence, as and when the individual functions have been strengthened, positive feed-backs may further strengthen the dynamics.

However, the internal dynamics is only part of the picture. There are factors influencing many TIS simultaneously, for instance institutional change in the form of tradable emission permits. These interact with internal processes and influence the evolution of a number of specific TIS. To make a distinction between the endogenous and exogenous, Geels (2002) conceptualise the technology-specific elements as a ‘niche’ and refers to ‘niche-internal’ processes and to the more general elements as ‘regimes’ and ‘landscapes’. The interplay between the ’niche’ and the regime (roughly sector, e.g. the agricultural sector) is a central part of the evolutionary process.

This distinction is useful and echoes the work of Myrdal (1957, p. 18) who showed a keen understanding of the interplay between internal and external sources of dynamics and even suggested that

> "… the main scientific task is…to analyse the causal inter-relations within the system itself as it moves under the influence of outside pushes and pulls and the momentum of its own internal processes".

In our framework of 'functions in innovation systems', the distinction between exogenous and endogenous is less visible but nonetheless there. Indeed, the whole notion of functions was developed to handle an integration of technology-specific and more general influencing factors (Johnson and Jacobsson, 2000, p.93):

> "In the context of an emerging technological system, we can define its borders by analysing what promotes or hinders the development of these functions. These factors may be fully technology specific, but may influence several technological systems simultaneously. Hence, they can be derived from a system perspective using different units of analysis: technology, industry, nation."

Hence, the driving forces and obstacles to system development are both technology-specific (endogenous in Geels' terminology) and general (exogenous). This means that within our framework, we incorporate determining factors found at the levels of 'regimes' and landscape' in Strategic Niche Management, although perhaps less visibly so. A technology-specific (endogenous) driving force may be demand from a leading-edge customer. At a higher system level (exogenous), the climate debate and accidents like that in Chernobyl are clear examples, both with consequent problems for the dominant regime. Indeed, Raven (2005) has a useful discussion of 'destabilisation' of regimes which opens up windows of opportunities for new 'niches'. This was, for instance, the case in Germany where the current regime (power sector) lost much legitimacy after the Chernobyl accident (Bergek and Jacobsson, 2003). [16]

From the perspective of an emerging TIS, it is particularly vital to identify blocking mechanisms, i.e. factors that provide obstacles to the development of powerful functions and, therefore tilt the selection environment in favour of incumbent technologies, and the dominant regime.[17] An endogenous blocking mechanism may, for instance, be poorly developed learning and 'political' networks that limit knowledge diffusion and legitimation.

An exogenous blocking mechanism may come in the form of highly organized incumbents that defend their markets and investments and make sure that institutions are continued to be aligned

[16] The stabilisation and destabilisation of the regime (and the dominant technology-specific innovation systems making up that regime), should perhaps be incorporated as a key process in industrial development.
[17] See Johnson and Jacobsson, (2000); Unruh (2002); Bergek and Jacobsson (2004).

to the dominant technologies. ‘Sailing ship’ effects (Rosenberg, 1976) through which the performance of conventional technologies are improved, may be another response from the regime, blocking the emerging TIS.[18] Further blocking mechanisms found at a higher system level may be traced to the emergence of other TIS that compete for space both in the market and in the political arena. A case in point may be the emphasis placed on gasification of coal in the US that may be a serious long term threat to gasified biomass in that it catches the attention of machinery suppliers that have capabilities to pursue other technological trajectories. Implicit in our framework is, therefore, not only considerations of dominant TIS in the regime but also of the impact of emerging, and competing, TIS.[19]

4. The evolution of the TIS – a successful formative phase and the beginning of a growth phase

In this section we apply our framework to analyse the development of the Swedish ‘bio-power’ innovation system. We divide the analysis in two parts where the first outlines a successful formative phase and a second focus on a current early part of a growth phase. The emphasis is on the latter part as it is most relevant to the objective of the paper (which is to identify key challenges for policy).

4.1 A successful formative period of 1980-2002

The first experimental developments in bio power in the district heating sector took place after the first oil crisis and one of the pioneers (VEAB in Växjö) took their first biomass CHP in operation in 1980 (Hellsmark, 2005). Another early mover was Borås that started to co-fire coal and biomass in 1984 (Peters, 2005). Prior to this, industry had started to establish biomass based CHP units. A major institutional change took place in the early 1990s when an investment subsidy scheme was set up for the period 1992-1997, i.e. a ‘market formation’ programme. This scheme was decided by a political coalition of three parties: Centre, Communists and Social

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[18] In the case of black liquor gasification, recovery boilers have improved their performance in generating power to such an extent that they constitute a serious threat to the emerging TIS (Modig (2005).

[19] We don’t exclude that the relationship between emerging TIS can be complementary. For instance, small-scale hydropower proponents and the advocacy coalition for wind power teamed up to influence the German legislation so that it would favour renewables (Jacobsson and Lauber, 2006). Sandén and Jonasson (2005) discuss how competition and collaboration evolved among emerging TIS in alternative fuels in Sweden.

Democrats. It was taken against the backdrop of the 1988 decision to start the dismantling of nuclear power, of a growing awareness of the role of fossil fuels in climate change (SOU 1992:90, p. 69) and a decade or more of efforts to reduce oil dependency whilst increasing the use of biomass (SOU 1992:90). As such, it gave a considerable strength to a legitimation process that the pioneers had long struggled with.

The efforts to reduce oil dependency had some effect on the use of biomass for heating purposes in the 1980s. This process was aided by the introduction of a CO_2 tax in 1991, a tax that was gradually increased in the 1990s (Riksskatteverket, 2003). This tax was conducive to a large scale diffusion of biomass in district heating but not to power production. As noted above, investment into new power production capacity was discouraged by the low power prices - for biomass CHP, the low price was broadly equal to variable costs only (Energimyndigheten, 2001, p. 57) and constituted no incentives for investors (Frost, 2005). Yet, new power capacity was needed if the decision to dismantle that nuclear capacity was to be implemented.

In other words, there were not only a powerful exogenous blocking mechanism in the form of low power prices, but also a set of important exogenous inducement mechanisms that involved a destabilisation of the current energy sector (Raven, 2005) and which provided a window of opportunity for bio power. Indeed, a commission that was appointed to assess the opportunities for bio power production found these to be substantial and it was suggested that support should be given primarily to CHP production using biomass (SOU 1991:93).[20]

The goal of the 5 year programme was to increase output with 1.5 TWh (0.75 TWh for bio power, Thornström, 2005) and it involved subsidies of SEK 1 billion (SEK 4000/kWe). A total investment volume of SEK 4.4 billion was distributed over 43 plants (Ds 2005:29 p. 83).[21] A second programme was designed for the period 1997-2002 with a total subsidy volume of SEK 900 million of which half was allocated to bio power (Ds 2005:29 p. 84). Including wind power and small scale hydropower, the goal of 1.5 TWh was met. At the end of the formative period,

[20] In an excellent study, it was also suggested that resources should be allocated to further development of gasified biomass (SOU:1991:93).
[21] Not all of these were biomass CHP. 24 were gas engine plants and 16 were bio power plants (of which four were in industry), see Ds 2000:20, p. 39. Additional CHP plants were built in the context of the second programme.

these new investments added to commercial investments in the paper and pulp industry and by about 2002, the output of bio power was estimated to 3.9 TWh (SOU:2001:77, p.143).

The programme, thus, influenced the ‘direction of search’ and a number of district heating companies turned to CHP production, as did some industrial firms. It also ‘mobilised a lot of financial resources’ and formed an enlarged market for the capital goods industry. The latter, in turn, led to a strengthening of other functions.

The capital goods sector had already a strong market position due to a large Nordic market for boilers (and some CHP units) in the paper and pulp industry (Olofsson, 2005; Ohlson, 2005) and in the large and expanding district heating system (Energimyndigheten, 2001) but now found an additional market for CHP. The Nordic countries housed several large firms (Kvaerner, Tampella and Ahlstrom) as well as some smaller ones. [22] The Nordic home market is very important for these firms. The paper and pulp industry has for long provided a sizeable home market and an opportunity to test new technology. In the 1980s, a political desire to reduce the use of fossil fuel (and introduce boilers with flexible fuels) and to reduce emissions, led to development of CFB boilers. A key driver of technical change is still the stringent regulations (e.g. emission constraints for power production) that influence the ‘direction of search’ and ‘knowledge formation’ (Olofsson, 2005).

At the end of the period, a Finnish firm, Wärtsilä, entered into the TIS through acquisition of another Finnish firm (Johnson, 2005). This is large firm specialising in decentralised power production. As there are large scale economies involved, CHP production in small scale tends to be expensive. In order to reduce the scale sensitivity, Wärtsilä developed a modular design approach that can lead to substantial savings in engineering and installation (Johnson, 2005). This was initially aimed at Nordic sawmills and smaller district heating firms (Johnson, 2005; Frost, 2005). Hence, the Nordic home market constitutes a seed-bed for ‘entrepreneurial experimentation’.

[22] Indeed, Kvaerner is the leading global supplier of biomass boilers for CHP (Olofsson, 2005).

Learning networks between industry and universities gained strength in the 1990s (Energimyndigheten, 2001; Olofsson, 2005; Peters, 2005). In particular, ‘competence centres’ are singled out as locations for knowledge formation, as meeting places and mechanisms for technology transfer. These were started in the mid 1990s as a science policy instrument (institutional change). ‘Knowledge formation’ in combustion engineering has for some time been substantial in industry and in universities (Energimyndigheten, 2001, Söderlund, 1997, Olofsson, 2005). Especially important is ‘knowledge formation’ about corrosion and high temperatures which is an issue of growing importance due to the need to use new types of fuel (e.g. waste) and to raise the power output. In the ‘competence centres’, essential links to material suppliers are fostered, links that are very important to the manufacturers of boilers (Olofsson, 2005). These ‘learning networks’ constitute channels for ‘positive external economies’.

Similarly, Borås Energy (a medium sized district heating and power company), has links to one of the competence centres. It has also developed strong relationships with the local college and influenced the educational programme towards waste management (an issue of importance as waste is used for fuel in their CHP plant (Peters, 2005).

Hence, whilst some investments in bio power plants had been made earlier, in both industry (Ohlson, 2005) and in district heating,[23] the two programmes created an enlarged ‘learning space’ in which the constituent components of the emerging system could be put in place. Thus, the formative phase saw significant changes in the three structural processes: institutional change, entry of firms and strengthening of networks. The system also achieved a great deal in terms of the seven functions: it formed markets, mobilised resources, influenced the direction of search, encouraged entrepreneurial experimentation, strengthened the process of legitimation and generated positive external economies. In conclusion, by the end of 2002, the formative phase had been successfully concluded. There was now a structure that functioned well and that had a capacity to ‘change gear’ and to shift into a growth phase.

4.2 The beginning of a growth phase

[23] In about 2000, there were 50 CHPs in industry (Energimyndigheten 2002, p. 56)

At the end of these two market formation programmes, there was a mix of institutional and other changes that not only opened up for more investments in bio power but also added uncertainty to investment decisions. In May 2003, a tradable green certificate (TGC) scheme was started whereby suppliers of ‘green electricity’, including bio power, were given a green certificate for each MWh they supplied to the net. These green certificates are then bought by power users who are obliged to fulfil a certain quota of ‘green power’. This quota is raised for each consecutive year. The scheme was initially limited to the period 2003-2010 but it is now proposed to be lengthened (SOU 2005; Regeringens proposition 2005/2006:154).

The goal of the TGC scheme was to add 10 TWh of ‘green power’ by 2010 to the assumed level of 6.1 TWh in 2002 (SOU 2001:77, p. 143).[24] This was suggested to be a large increase in the level of ambition as compared to the two programmes in the 1990s (SOU 2001:77). Most of the additional output was expected to come in the form of bio power as it was assumed to be the lowest costs alternative in this time period.[25] The expected price of the TGC was in the range of 50-200 SEK (SOU 2001:77, pp 175-176). So far, it has been slightly more than 200 SEK.

A second institutional change was the implementation of the emission trading scheme in Europe in 2005. This institutional change affects the price of power and with the (partial) integration of the distribution nets in Europe; it affects also power prices in Sweden, in spite of the marginal role of fossil fuel in the generation of power in Sweden.[26] Prices of emission rights have been much higher than expected and as from 2005, the emission trading scheme has added to an upward price pressure for power (Energimyndigheten, 2005a).[27] These prices have been raised greatly in comparison with those in the 1990s. Whereas the spot price for power at Nordpool was on average SEK 120 in 2000, it rose to 252 in 2002, 276 in 2005 and to as much as 406 in February 2006 (Nordpool, 2006).

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[24] The scheme excludes large scale hydro power.

[25] A closer inspection suggests that it was not a very ambitious goal. As was shown in SOU:2001:77, p. 143, the potential for expansion in current facilities amounted to 5.2 TWh which leaves only 4.8 TWh in new plants.

[26] Bo Källstrand, CEO of Swedenergy, suggests that the impact of Swedish power prices is as high as SEK 0.15 kWh (Källstrand, 2006)

[27] This is not the only underlying mechanism. “Despite well-filled reservoirs and good rainfall, electricity prices on the Nordic electricity markets are relatively high. The EU’s climate programme and the efforts to develop the internal market mean that the perspective must be widened in considering electricity prices. The trend in Sweden is not unique. The price rise at Nord Pool is identical to price trends on other electricity markets in Europe” (Energimyndigheten, 2005a, p. 6).

Taken jointly, the TGC and the recent rise in power prices to levels way beyond those in the 1990s has ‘influenced the direction of search’ and provided a powerful incentive for firms to both exploit existing capacity better and to invest in new (or modified) biomass fuelled CHP plants, in industry as well as in district heating systems. Indeed, these incentives led to a rapid increase in the production of ‘green power’; ‘market formation’ was significantly enhanced. In 2004, output reached 11.0 TWh out of which bio power constituted 8.2 TWh. The figure rose slightly in 2005 to 11.3 and 8.6 TWh respectively. Markets are now not only formed for large and medium sized plants but also for smaller plants (Johnson, 2005; Ohlson, 2005).

As it takes 3-5 years to go from the idea stage to implementation of a new CHP plant (Olofsson, 2005), these figures roughly reflect the installed capacity. The effects of the new incentives on new investments will begin to be seen only in the second half of the decade. Hirsmark and Larsson (2005) surveyed the district heating suppliers and (with a very high response rate) they estimate that another 4 TWh (excluding waste) will be added to the power output in district heating systems by 2010. In industry, a similar survey conducted in 2004, suggested that output will increase by 2.3 TWh. To the extent that these predictions are broadly right, production of bio power could amount to about 15 TWh already in 2010. This would be equal to nearly all of the expected production of ‘green power’ (i.e. including also wind and small scale hydro power) under the original TGC scheme (the total supply was expected to be 16.1 TWh in 2010, see SOU 2001:77, p. 145).[28] Interviews with a number of district heating companies confirm that there is large interest in bio power and that new investments are either decided on (e.g. Frost, 2005; Johansson, 2005; Johansson 2005a) or are carefully assessed (Peters, 2005, Stigmarker, 2005). Clearly, the TGC and tradeable emission rights have a powerful effect on ‘influence the direction of search’.[29]

The TGC leads, of course, to a very substantial ‘resource mobilisation’. For instance, an annual trade in 10 TWh, at a price of SEK 200/MWh, involves a sum of SEK 2 billion (p.a.). ‘Market

[28] The assumed production of ‘green power’ from small scale hydro and wind amounted to 2.2 TWh and these are expected to grow within the TGC scheme. Hence, the quota in the original scheme would not be sufficient to absorb all the supply of green certificates.

[29] In addition, there is a genuine environmental awareness among some local councils that give strong signals of support to CEOs of local CHPs to invest in biomass plants (Frost, 2005; Johansson, 2005; Johansson, 2005a)

formation' also encourages 'entrepreneurial experimentation' and associated applied 'knowledge formation'. Two instances are the modularisation work of Wärtsilä and efforts to increase the steam pressure (so that more power can be generated, Olofsson, 2005). Both will increase the attractiveness of bio power and, hence, further 'market formation'. We can, therefore, begin to identify positive feed-backs in the system. The hitherto largely exogenous inducement mechanisms are beginning to be supplemented by endogenous ones-a beginning of a momentum can be identified.

4.3 Technology competition and emergence of new 'blocking mechanisms'

Yet, other institutional changes have generated 'blocking mechanisms' that threaten to obstruct this momentum and the realisation of the long term potential of bio power (which is higher than 15 TWh, see section 2). In the political agreement of 1991 that lay the foundation for the two subsequent market formation programmes for bio power, a decision was taken not to support the diffusion of fossil gas (Jonason and Sandén, 2005). Fossil gas was introduced as late as in 1985 and the pipeline was initially limited to the south-west part of the coast where a number of gas powered CHP plants were built. The choice of supporting bio power instead of fossil gas was presumably the 'price' paid to the Centre party for a less antagonistic position vis-à-vis nuclear power (Moberg, 1991).

An important element of the political agreement of 1991 was the introduction of a CO_2 tax. This tax was gradually increased in the 1990s and provided a powerful and effective incentive to move from fossil fuel to biomass in district heating (see section 2). Ten years after the political agreement, the position of the government had, however, wavered. This is clearly seen in three recent texts from the government. In a text from 2001 (Prop. 2001/02:143, pp 53-54), the government argues that:

"With today's energy taxes, it is not profitable to build new fossil fuelled CHP plants…Poor profitability in the fossil fuelled CHPs may, in the longer run, lead to ….dismantling of these. This may lead to a reduction in energy security…in particular in Southern Sweden, at the same time as the environmental effects would be negative since they are plants with often have very high efficiency…On the margin, the reduction in power output would have to be replaced by imports of environmentally poorer power production in coal fired power stations" (my translation).

In order to ensure a high capacity utilisation of the existing fossil fuelled CHPs on the southwest coast, and to provide incentives for Gothenburg Energy (also on the southwest coast) to build a new CHP plant with a capacity to supply 1.5 TWh, the government advocated a tax reduction for fossil fuelled based (in practice gas) CHP production. The benefits would be twofold, an increase in power supply and a reduction in CO_2 emissions.

The same text reappears in FI 2002/2635 (p. 7) but here the perspective is shifted from a largely defensive position of using existing capacity to a more offensive that emphasises more the need for new investments. Finally, the Government proposition (PROP.2004/05:1, p. 56), refers to a 'balanced expansion' of the infrastructure for fossil gas. Also in this text, there is a reference (p. 45) to a reduction in need to import power and, consequently, a reduction in CO_2 emissions abroad.

Hence, the utilisation of existing plants and a 'balanced expansion' of the gas infrastructure are motivated by both energy security and reduction in CO_2 emissions.[30] Indeed, the pipeline is now being extended from the south-west coast northeast in the direction of Stockholm. There are also plans, dating back some time (Dagens Nyheter, 1998) to link up to a Russian pipeline to Germany and supply the Stockholm region with gas.

The proposed tax reduction resulted in a law that as from January 1st, 2004, meant that CHP production pays no more energy taxes and that the CO_2 tax was reduced by three quarters for fossil fuel CHPs. An unexpected rapid rise in the price of gas from about the mid 2004 (gas prices follow oil prices), led to a reduction of the CO_2 tax to nil.

This shift in policy was taken in a context that has both national and international components. The proponents of gas (including President Boris Jeltsin) had, of course, lobbied a great deal. Particularly important was the lobbying of Göteborg Energi who saw the CO_2 tax as the prime obstacle to realising their investment plans for a large gas fired CHP. In 2000, they devised a strategy to overcome this barrier and worked together with local politicians as well as with three

[30] This is an argument put forward already in the 1990s by the gas industry (see e.g. Göteborgsposten, 1997).

industry associations (Swedish Gas Association, Swedenergy and the Swedish District Heating Association). A common position was sought and eventually was formed as one where tax legislation for CHP connected to district heating would be the same as for CHP in industry (Hellsmark, 2005).

Presumably, this lobbying work was strengthened by an earlier critique from the Commission about the Swedish tax policy that discouraged power production in district heating systems (Andersson and Werner, 2000). A strategy from the EU to increase CHP production put additional pressure on Sweden, which was used by advocates of CHP (see e.g. Rundström et al, 2002).[31] These pressures coincided with renewed tensions at the 'regime' level where Sweden had begun to import (dirty) power (thus, the concern with CO_2 above) at the same time as the government had decided to dismantle two nuclear power plants in the South of Sweden, jeopardising the regional power balance (thus, the energy security concern above). Gas was then seen as the quickest and most cost efficient way of substituting for nuclear power (Thornström, 2005) and the suitable application was in the form of CHP, given the large district heating system. The former Minister of Industry, Leif Pagrotsky, expressed this clearly (Pagrotsky, 2004):

> "I assess that the use of natural gas has to be allowed to increase in a balanced way if nuclear power is to be replaced. I will therefore work for an increase in the use of natural gas" (my translation).

Although referred to in the Government proposition (PROP.2004/05:1, pp.70-71), the link to the nuclear issue was, however, obscured by referring to a reduction in CO_2 emissions as the motive (by replacing coal power either through import substitution or by exports).[32] Knutsson and Werner (2002) show, however, that this argument is not particularly convincing. Whereas gas CHP produces more power than biomass fuelled CHP (since it can use a combined cycle of gas and steam turbines), it emits CO_2 whereas biomass fuelled CHP has no CO_2 emissions. If on the margin we have coal power, the two alternatives are broadly equal in terms of CO_2 emissions but if gas power is the marginal source of power, then biofuelled CHP fares best. Hence, it appears as

[31] These advocates (Swedenergy, Swedish District Heating system and Svenska Kommunförbundet) were not necessarily advocates of gas CHP but of CHP in general. Indeed, they point out that from a CO_2 perspective, there is no difference between gas and biofuel.
[32] Interestingly, the option to increase biopower was not included in the analysis.

if the argument of the government to change the tax structure and provide greater incentives to investors in gas CHP is faulty.

Again, we can see how the nuclear power issue shapes Swedish energy policy.[33] In order to provide a quick solution to tensions at the regime level, it opens up for a substitute to bio power precisely at the point in time when the TIS for bio power shifts over to a growth phase, induced by another institutional change, the TGC. The opening up for gas is, of course, a critical issue for the future of bio power as the proposed pipelines will go through areas with a large potential for bio power.[34] With the very rapid response to the TGC, as described above, the quota for 2010 is likely to be more than filled and the incentives for bio power investment will depend on how the new quotas are set. A recent proposal suggests that they will be raised by another 7 TWh for until 2016 (Regeringens Proposition 2005/2006:154). It is an open question if this will be enough to prevent gas CHP to gain market shares.[35]

These recent changes in the tax structure clearly suggest that the process of ‘legitimation’ of bio power is far from complete. Indeed, a ‘battle over institutions’ is currently underway, the outcome of which is highly uncertain and which depends in part on the relative strength of various ‘advocacy coalitions’. In the context of a decades long ‘nuclear trauma’ (Jacobsson and Bergek, 2004), biopower have always been met with resistance among advocates of nuclear power. [36] A particularly telling example is an editorial in the leading daily newspaper Dagens Nyheter (1997) which, quite erroneously, claimed that:

> “Firewood can’t replace nuclear power…Biofuels can give us a marginal addition, but not even with maximum production can they, with respect to power, replace more than one nuclear power reactor (my translation)”**.**

[33] See Johnson and Jacobsson (2000 and 2003) for more examples.
[34] The timing is very unfortunate as many district heating plants were built in the end of the 1970s and 1980s and these need now to be replaced (Frost, 2005).
[35] Had the price of gas not risen lately, it is likely that more firms would opt for gas CHP, pre-empting the market for biomass CHP. If this were to happen, the TGC quotas would have be filled by wind power, in particular off shore. Such investments have even longer lead times than bio power which would have put the whole TGC scheme in jeopardy.
[36] This trauma has been created by a pressure to dismantle the nuclear power stations which run with a very low marginal cost and replacing that power production by new plants with a higher average cost. For a clear statement of the reaction from industry to such plans, se Svanholm (1997).

Advocates of fossil gas partly overlap with these (e.g. Swedenergy and Eon) but include also other actors. These are e.g. Swedish Gas Association, Swedish District Heating Association, Gothenburg Energy and Fortum. Some of these have links to foreign gas suppliers, such as Gasprom.

At the same time, the main actor advocating bio power, SVEBIO, is divided.[37] First, with the liberalisation of the power market in the 1990s, larger utilities (some of the utilities favouring nuclear and/or gas are also members of SVEBIO) have acquired some of the pioneers in bio power and reduce the strength of its advocacy coalition (Kåberger, 2004). Second, the paper and pulp industry is an advocate of biomass but has always been strong proponents of nuclear power.

5. Policy challenges

As from 2003, bio power is in a growth phase and the TIS has begun to realize its large potential. Yet, there are many obstacles to a further diffusion and in this section we will discuss four main challenges for policy makers.

5.1 Extremely high wind fall profits in a 'cost-efficient system'

The proponents of tradable green certificates argued that this is a cost-efficient system as it promotes the currently most efficient technologies (SOU 2001:77). In contrast to a feed-in-law, a 'market based' instrument of this kind requires an initial liquidity. Creating this liquidity is associated with very high costs and very large 'wind fall profits'.

As it may take more than three years for a new plant, say a CHP plant, to be erected, an initial liquidity presupposes that a number of existing installations are allocated green certificates at the start of the implementation of the system, in the Swedish case in May 2003. Only then can the market mechanism work. This was an important reason behind the decision to include the considerable stock of bio power plants in the system (Ds 2005:29, p. 89).

[37] Whilst a divided SVEBIO was able to oppose a first attempt to change the tax structure (the SNED enquiry), they failed to stop the second attempt (Kåberger, 2004).

These plants were of different character. Some of them had received investment subsidies in the 1990s whereas others were pure commercial installations (mainly in industry). In about 2002, the installed bio power capacity was estimated to be about 3.9 TWh, most of it in industry (SOU 2001:77, p. 143). In addition, 4.2 TWh were estimated to be available with little or no investments:[38]

> "Our assessment is that an expansion of existing plants can take place soon after the introduction of the certificate system. It can take place with modest or no investments…for example through changing fuel and increasing the number of hours with full load." (SOU 2001:77 p. 144, my translation)[39]

The draw back is, of course, that if plants that already have been invested in are allocated green certificates, resources are channelled to their owners without a corresponding effort in terms of investing in new capacity. This appears not to have been an issue when the system was initiated. In the first follow-up of the tradable green certificate system, which proposed a lengthening of the time horizon to 2031 and with an experience of prices at SEK 200 per MWh or more, the whole issue was underlined for the first time (Ds 2005:29):

> " The most obvious disadvantage ….is that consumers…not only pay for new investments…but they will also, for a long period of time, support current plants that in many cases already have a good profitability at current power prices and in combination with other policies."

The follow-up study (and subsequently the Government, see Regeringens Proposition 2005/2006:154) proposes to limit the inclusion of such plants to 2012 and 2014 (the former for commercial plants in the paper and pulp industry and the latter for those that received investment subsidies). These plants would, therefore, generate wind fall profits for a substantial period of time. In what follows, we will estimate the size of these.

In 2004, the number of certificates given to producers of bio power amounted to 8.2 million. This equals a bio power production of 8.2 TWh (which is nearly exactly the sum of the short term potential as discussed just above). As the lead time for new investments is counted in several years, it is clear that the power producers responded very rapidly to changing incentives

[38] This refers to bio power only.
[39] A similar assessment was made in 1995 (SOU 1995:139, p. 131).

and realized the potential of existing plants.[40] In our calculation, we assume that this represents the potential of plants that existed in May 2003.

The calculation is different for 2003/2004 and for the period thereafter. For the first two years, we have data on actual transactions in green certificates and the average price of these. Multiplying these (the price was about SEK 200) gives a wind fall profit of about SEK 400 million in 2003. In 2004, the price was SEK 231 and the wind fall profits 2.6 billion.[41] For the period 2005-2013 (we simplify by using that year) we calculate with three prices for the certificates, SEK 150, 200 and 250. For the whole period of 2003-2013, the total figures would amount to SEK 14, 18 and 21.5 billion. [42]

Whatever the outcome within this range,[43] the cost for society of creating a 'liquid market' is, of course, astonishingly high. This is a particularly noteworthy feature for a system that was promoted as cost-efficient. In this context it is useful to note what proponents of the certificate system wrote in 2001:

> " in the concept of efficiency we also include that the total cost of promoting an expansion of power from renewable energy sources should be as low as possible (SOU: 2001:77, p. 125, my translation).

The main draw-back of this high cost is not, however, neither the massive shift of resources from consumers to plant owners (mainly in the paper and pulp industry) itself, nor that it will damage the credibility of the certificate system but that it may threaten the process of 'legitimation' of bio power and other renewables. A key challenge for policy makers is, therefore, to design policies that do not create wind fall profits of this magnitude.

5.2 Inherently large uncertainty in policy dependent TIS?

[40] Interestingly, Hirsmark and Larsson (2005) suggest that output amounted to 6.5 TWh out of which 4.2 TWh was in industry and 2.3 TWh in the district heating sector.

[41] We assume here that the share of bio power in transactions of certificate is the same as its share of allocated certificates.

[42] As 60% of all bio power production takes place in industry, most of these windfall profits accrue to the paper and pulp industry (Ds 2005:29, p. 40). Resource flows of this magnitude are not necessarily negative though if the funds are used to invest in new capacity and provide incentives for firms to do so in an early phase of the development of a TIS.

[43] Interestingly, Ds 2005: 29, p. 98 discuss a range prices for green certificates of SEK 100-400.

Uncertainties are, of course, inherent in a market economy. Without uncertainties, there would be no room for entrepreneurs and it is clearly neither desirable, nor does not fall upon the government, to eliminate that uncertainty. Yet, in the energy sector, it is evident that government policy has increased uncertainty for investors to a point where it constitutes a ‘blocking mechanism’ that is detrimental to a transformation process.

For investors, it is a lack of stability in the policy environment (e.g. frequent changes in taxes etc) that has, for long, generated a level of uncertainty that has had a dampening effect on investments. This is not a new observation but rather on that has been made over and over again at least since the early 1990s (and probably before). For instance, as argued in a preliminary report of the Bioenergy Commision (SOU 1991, page 40):

> “A conclusion from this chapter is there is great uncertainty as regards the conditions for biofuel based power production. The uncertainty is probably larger than what can be seen as normal for firms that have to take decisions in this field” (my translation).[44]

More than five years ago, Johnson and Jacobsson (2000) identified a range of ways in which policy compounded uncertainties in the field of renewable energy and a recent enquiry into the potential for CHP underlined this problem again (SOU 2005:33, p. 142):

> ” ..the basic problem is the uncertainty in the conditions for investment in CHP plants. These uncertainties refer to changes in taxation, environmental demands, regulations, costs but can also be the development of the power market and support systems that influence the profitability of an investment” (my translation).

Interviews with managers of CHP plants confirm this (e.g. Stigmarker, 2005; Johansson, 2005) and suggest that additional sources of uncertainties are found in the characteristics of the new policy regime dominated by tradable green certificates and tradable emission rights (see also

[44] See also SOU 1992 (pages 339 and 364); Elforsk (2003, p. 10); Bengtsson (2003, p. 35)

Elforsk, 2005). Whereas the prices of these are currently higher than expected, the longer term prices are subject to much uncertainty.[45]

Much of the uncertainty over the price of green certificates stems from an inability of central planners to design a supply curve (Jacobsson, 2002). With long lead times for investments, an inherent uncertainty of the response of managers to a given set of incentives (Jacobsson and Bergek, 2004), and unknown supply constraints in the machinery industry (Energimyndigheten, 2005; Stigmarker, 2005), it is extremely difficult to predict the evolution of price for the certificates.

Indeed, more than one manager remarked that the currently high prices constitute a serious threat to these two systems (Stigmarker, 2005). Of course, a doubt over the longer term viability of these two support systems introduce yet additional uncertainties for investments with 20 years life time. Adding these uncertainties to the conventional ones in the business, suggests that making investment calculations in CHP plants is fraught with extreme difficulties. Investment decisions are, therefore, often taken on the basis of intuition and beliefs, if taken at all (Stigmarker, 2005; Johansson, 2005). A key challenge is therefore to design policies that do not compound the 'normal' uncertainties for firms in the energy field or is it inherent in policy dependent TIS to have a very high level of uncertainty?

5.3 Emergence of competing technologies, the process of legitimation and the 'politics of expectations'

The extreme turbulence, driven by conflicting institutional changes and large price changes, and associated uncertainties in the period following the start of the TGC scheme is a recent case in point of largely policy driven uncertainties. After much lobbying, an enlarged market space was made available to fossil gas, just as bio power was poised to move into a growth phase. Today, the combination of high gas prices and high prices for power and TGCs means that bio power seems to be most attractive (Elforsk, 2005) but the longer term uncertainties are substantial.

[45] An additional source of uncertainty is the future distribution of tradeable emission rights for new power plants – an extremely important variable for investors (Stigmarker, 2005).

This confluence of events highlights not only uncertainties but the importance of an incomplete 'legitimation process' for bio power. The recent tax changes may well be interpreted as an indication that the Government has been, to an extent, 'captured' by advocates of fossil gas. From the point of view of bio power, the policy challenge is to secure a much larger market space and avoid that to be pre-empted by tying up a sizeable part of the district heating systems to gas suppliers.[46]

In a recent proposition (2005/06:154), the TGC quota is raised for 2015 so that an additional (to the assumed level in 2002) 17 TWh of 'green power' is to be generated (ending up with a total supply of about 23 TWh).[47] Yet, if bio power production will amount to 15 TWh in 2010 and the current production of small hydro and wind power of 3 TWh is raised to 4 TWh in 2010, an additional 4 TWh only will need to be generated in the period 2011-2015. With current plans to raise wind power output to 10 TWh by 2015, there may be an over supply of certificates at the end of the period. Although Ds (2005:29) correctly warns of the difficulties of estimating the supply curve, a high ambition level is probably necessary in order to pre-empt gas from capturing market shares (however, at the risk of insufficient supply of TGCs and prices that threaten the whole scheme). As underlined in section 2, the longer term potential of bio power is much larger than 15 TWh and the challenge for policy makers is not to fill a quota for 2015 but to secure the longer term conditions for realising this potential.

A central task here is to manage the 'politics of expectations'. These form a part of 'influence the direction of search' and, indirectly influences the process of 'legitimation'. Hence, a key process is how expectations are formed and articulated (Raven, 2005; Negro et al., 2006)**.** One way is which these are formulated and communicated is in the form of various enquiries. Scrutinising a number of these reveals an interesting pattern. Some convey a very limited potential. For instance SOU (2001:77, p. 143) suggests that the potential for biopower is about 12 TWh whereas Elforsk (2003) writes (concerning district heating only but for all CHP) that

[46] As will be explained below, securing a market space may involve another type of gas, namely gasified biomass.
[47] This is 2 TWh more than what was suggested in Ds (2005:29) which warned against raising the level of ambition further than so.

> ” The physical limitation depends on the development of the hot water base. As physical limitation could also be included existing hot water boilers in the district heating systems….with an expected expansion of the district heating it can be assumed that the volume (of power) can be increased to 9 TWh per year) by 2010.

A similar formulation is found in the Government proposition (2001/02/143, p. 86) which in the context of a discussion of the potential for renewable energy writes that

> “The Government has over a number of years supported biomass based CHP. In CHP, the biomass is used with a very high efficiency. The available heat base sets, however, an upper limit to how much power can be generated with such a high efficiency”.

Whilst technically correct, these citations portray a picture of a potential that is tightly constrained by the district heating system and not the more appropriate image of a greatly underutilised potential.

Yet others go beyond short and medium term constraints and point to much larger long term potential. We have already in section 2 referred to Knutsson and Werner’s study (2002) of a potential of about 12 TWh in district heating only and the Swedish District Heating Association (2004) has a similar view. Moreover, the latter underline that in the longer term, district heating could move from today’s 50-55 TWh heat supply to 80 TWh which, of course would increase the potential further (although not necessarily in a linear way). A part of the challenge to realise the long term potential of bio power is, therefore, to manage the ‘politics of expectation’ by developing a vision of bio power as a stable contributor of a sizeable number of TWh in the future. This vision may then underpin present and future policies.[48]

5.4 The still embryonic stage of gasified biomass

[48] Part of these policies would be to ensure that the behaviour of some larger district heating firms does not jeopardise the reputation and legitimacy of district heating (Johansson, 2005) There has recently been an uproar against the pricing policies of some of the larger firms which resulted in a parliamentary enquiry (SOU 2005:33). Andersson and Werner (2005) show how the concentration ratio has increased after the deregulation and Johansson (2005) suggests that this concentration is detrimental to the reputation of district heating. Another part would be to increase the potential by changing the tax laws so that industry has to pay energy and CO_2 tax (Johansson, 2005; Frost 2005; Stigmarker, 2005, Peters, 2005).

In an excellent review from 1991, i.e. before the two subsidy programmes for conventional steam cycle bio power, a bioenergy commission pointed to a range of activities in gasified biomass in Sweden, dating back to at least 1980 (SOU 1991:93). As mentioned in section 2, the advantage with a combined cycle is that the power-to-heat ratio can be substantially increased. Two technical trajectories were followed, a pressurised and an atmospheric. The former was large scale and the latter more suitable for medium sized plants. The two largest utilities chose the pressurised technology, presumably since the government had decided to actively promote the phasing-out of nuclear power which generated a need for bioenergy technologies with high electrical efficiency. A demonstration plant was built in Värnamo and another one was planned.

The largest utility, Vattenfall, rejected the atmospheric technology (developed by Studsvik) but Shell suddenly chose that process over other available technologies for a project in Brasilia. The Shell project provided Studsvik with the legitimacy it needed to attract more customers, and, thus, potential shareholders for a take-over. In 1992, a number of companies with interests in the energy field provided the capital to form TPS, which took over the atmospheric gasification technology.

There was a substantial interest in the atmospheric gasification technology from several medium sized district heating producers (Peters, 2005; Johansson, 2005). One of those was Borås Energi that not only conducted a feasibility study but prepared for an installation by buying a large drying unit. The management also spent a great deal of time trying to secure funding but failed to convince policy makers and firms to provide funding, (above a 50% subsidy) that could reduce the risks for the medium sized council owned CHP firm (Peters, 2005). Hence, this firm, and others, attempted to influence the evolution of the atmospheric gasification trajectory, much in line with the recommendations of the Bioenergy Commission of 1991 (see page 87). However, unlike the larger utilities, firms of this size can’t handle the inherent uncertainties of investing a great deal of money in unproven technologies. Borås Energi (and others) then decided to temporarily drop the gasification technology and await the experience of TPS in two plants abroad. Thus, in spite of an availability of leading edge competence, no domestic plants were built.

The pressurised gasification technology resulted in one[49] successful demonstration plant, delivered by the Finnish firm Ahlström (Ohlson, 2005a) but the focus of the plant is today on developing a gasification process for alternative transport fuel.[50] Hence, the focus shifted some years ago from power production to fuel production and the atmospheric trajectory gets very little attention, apart from a few co-firing plants (Ohlson, 2005a).

Biomass gasification, thus, has a long history in Sweden (and in Finland). Indeed, Sweden and Finland have developed a unique competence in biomass gasification. Taken jointly, these countries had 13 per cent of the world's scientific publications in the period 1980-2005 (Badhan, et al., 2005) and 16 per cent of the patents in biomass gasification in the period 1976-2005 (Nielsen, 2005).[51] Key industrial actors are also located in the two countries (Chemrec, Kvaerner, Foster Wheeler, TPS etc). In a world that trying to grapple with the climate issue and where oil and fossil gas are likely to be both very expensive and subjected to growing insecurity in supply, this competence base has a potential to become very valuable. Indeed, with a growing integration of the Nordic power net with the Continental one, very large export opportunities open up for 'green power' (Ohlson, 2005).

Yet, global patenting reached a peak in 2000 and so did Nordic patenting. Larger firms in the Nordic countries either ceased their activities or reduced them (Olofsson, 2005; Ohlson, 2005). At the same time, it appears as if gasification of coal is the dominant path, at least in the US and China. The larger Nordic firms are, of course global players and it is not self-evident that they will opt to develop a risky technology which is not to be expected to be the dominant one globally.

Similarly, potential customers, such as local utilities, are not prepared to take the risks associated with being the first customer. This is particularly so for smaller utilities who need access to external risk sharing actors for future investments in new technology (Johansson, 2005). A final key challenge for policy is, therefore, to create appropriate conditions for exploiting the Nordic

[49] Vattenfall, having rejected the atmospheric technology, subsequently abandoned its plans for a full scale unit (60 MWe) of pressurised technology due to a large supply of power in Sweden at that time (SOU 1992:90, p. 352).
[50] This is the recent focus also of the efforts to use black liquor in a demonstration plant in Piteå, which is another prominent trajectory in biomass gasification. Black liquor is a residue from paper and pulp manufacturing.

[51] The patent analysis used US patents.

knowledge base and to develop a viable alternative to natural gas and to gasified coal for power production. This would involve not only maintaining the competence base in pressurised gasification technology, e.g. by setting up a specialised R&D company in this field (Ohlson, 2005) but also to put the atmospheric design alternative back on the track by sticking to the recommendations of the Bioenergy Commission of 1992 (SOU 1992:90, p. 352). Clearly, there is still an interest in gasified biomass from solid fuel among both suppliers of equipment and customers (power utilities) but the risk issue is still there as a 'blocking mechanism' for the relatively smaller firms that may adopt the atmospheric pressurised technology. By designing a policy that manages that risk, 'market formation' and 'entrepreneurial experimentation' may be encouraged and the potential for bio power be yet further enlarged.

6. Conclusions

The purpose of this paper was to analyse the evolution of this 'bio power' innovation system and to specify the key policy challenges for realising the large potential of bio power in Sweden. Using a technology-specific innovation system approach, we outlined a long and, eventually, successful formative phase that ended in 2002 with an embryonic system that had been put in place (although with a very strong actor base in the form of a capital goods sector). With two institutional changes (TGC and tradable emission rights), the bio power innovation system could shift into a growth phase. The functions of the system were strengthened and positive feed-back loops became visible. Yet, simultaneously, other institutional changes opened up for fossil gas to become a strong substitute to bio power. A 'battle over institutions' is, thus, currently taking place between advocates of fossil gas and bio power.

Four challenges were identified for policy makers. Whilst TGC strengthened the functions of the system, it will also lead to wind fall profits of a scale that threatens the legitimacy of not only the scheme but also of renewable energy technology. A first challenge for policy makers is, therefore, to design policies that do not create wind fall profits of this magnitude. For many years, the level of uncertainty for investors in the energy field has hampered investments. The recent two institutional changes only add new sources of uncertainty, making investments more of an act of faith than the consequence of an economic assessment. A second challenge is to design policies that do not compound the 'normal' uncertainties for firms.

The decision to open up for a larger scale introduction of fossil gas not only adds to this uncertainty but reflect an incomplete process of legimitation for bio power and a lack of long term vision of the role of bio power in the Swedish energy balance. The challenge is to secure markets for bio power that reflect its potential and not allow gas to pre-empt these. A part of that challenge is to handle the ‘politics of expectations’. Whereas the longer term potential of bio power is large even for conventional steam cycle technology, it is even larger with gasified biomass. The Nordic countries have a long history and a strong competence base in this technology. The challenge is to put this technology back on the track of power generation.

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