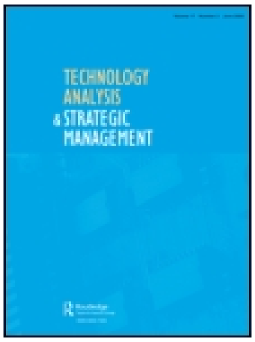

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Explaining the success of emerging technologies by innovation system functioning: the case of biomass digestion in Germany

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We examine the view that the success of emerging technologies may be understood using a technological innovation systems analysis, drawing on a system functions approach. This is done in the context of a case study of the successful diffusion of biomass digestion technology in Germany. We show that that all system functions that are claimed to be important within the innovation systems approach are present in the German Biomass Innovation System; and that these system functions positively interact leading to virtuous cycles and a rapid growth of the German Biomass Digestion Innovation System.

Keywords: emerging technologies; innovation system; system functions; biomass

1. Introduction

During the last decades the innovation system approach has become a well-established heuristic framework that presents insight in the factors that explain processes of innovation (Lundvall 2002). This framework has proven to be successful for policy purposes; it has been adopted as an analytical framework and guideline for science and innovation policy making by numerous public organisations around the world (Albert and Laberge 2007).

In spite of this success, the innovation system approach is still associated with conceptual diffuseness. One line of research, proposed by Edquist (2004), is therefore to make it more clear and consistent so that it will serve as a basis for generating hypotheses about specific variables within innovation systems. He states that one way to increase the rigor and specificity of the innovation system approach is to relate innovation systems explicitly to general systems theory, as has been done to a much larger extent in natural sciences than in the social sciences.

One of the characteristics of a 'system' is that it has a function, i.e. it performs or achieves something. However, this has not been addressed systematically in earlier work on innovation systems. Galli and Teubal (1997) focused their thoughts in this direction, and this was followed

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up by Johnson (1998), Jacobsson and Johnson (2000), Liu and White (2001), and Rickne (2001). These authors claim that several system functions are considered important for an innovation system to develop and thus increase the success chances of the emerging technology. They propose a conceptual model in which the satisfactory fulfilment of several system functions has a positive influence on the development and diffusion of innovations.

This line of research has attracted much attention by scholars interested in understanding the driving forces and the blocking mechanism that influence the development and diffusion of sustainable technological trajectories (Foxon et al. 2005; Suurs and Hekkert 2005; Alphen, Hekkert, and Sarke 2006; Bergek, Jacobsson, and Sanden 2006; Markard 2006; Hekkert et al. 2006; Negro, Hekkert, and Smits 2007a; Negro et al. 2008). Even though the results are promising there is one issue that remains problematic. Most studies focus on technological trajectories in an early state of their emergence. The logical consequence is that the diffusion level of innovations is low. This makes it difficult to test the proposed conceptual model. Thus, what is needed to propel this line of theory development further is an analysis of empirical case studies of successful technological trajectories.

For that reason in this article we analyse the evolution of biomass digestion in Germany. The diffusion of this renewable energy technology is a great success compared to diffusion in other European countries. By analysing the functioning of the German biomass digestion innovation system over time we aim to test whether the claims about the importance of innovation system functioning will hold.

The research question of this paper is:

> *Can the successful diffusion of biomass digestion in Germany be explained by a well-functioning innovation system*?

The paper is structured as follows: an overview of the background of the innovation system approach and the system functions concept is given in Section 2; the focus being on the functions that are used in this paper. The methodology applied is then described in Section 3. The technical aspects, event description of biomass digestion in Germany and the function fulfilment can be found in Section 4. Section 5 contains the conclusions and lessons learnt from the German case.

2. Innovation systems and system functions

There are several definitions of innovation systems given in literature, all having the same scope and all derived from one of the first definitions (Freeman 1987, 1): '…Innovation Systems are networks of institutions, public or private, whose activities and interactions initiate, import, modify, and diffuse new technologies.'

Usually, when innovation systems are studied on a national level, the dynamics are difficult to map because of the vast amount of actors, relations, and institutions. Therefore, many authors who study and compare National Systems of Innovation (NSI) focus on their structure. Typical indicators to assess the structure of the NSI are R&D efforts, the quality of educational systems, collaborations between universities and industry, and the availability of venture capital. Thus, most empirical studies on innovation systems do not focus on mapping the dynamics (Hekkert et al. 2006).

However, in order to understand technological change we also need insight into the dynamics of the innovation systems. To understand technological change the technological innovation system (TIS) is the right unit of analysis (Hekkert et al. 2007). The TIS is defined by Carlsson and Stanckiewicz (1991, 94) as: 'a network or networks of agents interacting in a specific technology area under a particular institutional infrastructure to generate, diffuse, and utilise technology'.

This implies that there is a technological innovation system for each technology and that each innovation system is unique in its ability to develop and diffuse a new technology (Jacobsson and Johnson 2000). When the TIS is in the early stages of emergence the number of actors, networks, and relevant institutions is much smaller than in a NIS; which reduces the complexity. This makes it possible to map the dynamics of an emerging TIS.

A well-functioning TIS is a requirement for the technology in question to be developed and widely diffused. In fact, large-scale diffusion cannot take place without a well-functioning TIS, but what is it that determines whether or not a TIS functions well and how do we find out? One option is to study the end result, namely the diffusion of the technology. However, for emerging innovation systems this is not a viable strategy because diffusion by definition does not yet take place.

Edquist (2001) states that determining factors can be traced by identifying the key activities that take place within the TIS that influence the development, diffusion, and use of an innovation. These activities are also called 'functions of innovation systems' ('system functions') by other authors. Jacobsson and Johnson (2000) developed the concept of system functions in which a system function is defined as '…a contribution of a component or a set of components to a system's performance' (Bergek 2002, 21). They state that a TIS may be described and analysed in terms of its 'functional pattern', i.e. how these functions have been served (Johnson and Jacobsson 2002, 3). The system functions are related to the character of, and the interaction between, the components of an innovation system, i.e. actors (e.g. firms and other organisations), networks, and institutions, either specific to one TIS or 'shared' between a number of different systems (Edquist 2001).

Several recent studies applied the system functions approach, which has led to a number of system function lists in the literature. This creates unanimity about which system functions are relevant. This paper uses the recently developed list of system functions at Utrecht University (Suurs and Hekkert 2005; Hekkert et al. 2006; Negro, Hekkert, and Smits 2007a; Negro, Hekkert, and Smits, in press) that will be applied to study the functioning of the German Biomass Digestion Innovation System over time.[1]

Function 1: Entrepreneurial activities

The existence of entrepreneurs in innovation systems is of prime importance. Without entrepreneurs no innovation would take place and the innovation system would not even exist. The role of the entrepreneur is to turn the potential of new knowledge development, networks and markets into concrete action to generate and take advantage of business opportunities.

Function 2: Knowledge development **(***learning***)**

New knowledge needs to be developed if solutions to the identified problems have to be provided, i.e. the development of a new technology, in which the development of scientific and technological knowledge is crucial. Possible sources of new knowledge are R&D, search and experimentation, learning-by-doing/using and imitation, where the combination of old and new knowledge in innovative ways and the reuse of old knowledge by imitation are included.

Function 3: Knowledge diffusion through networks

The essential characteristic of networks is to exchange information. The diffusion of information through networks, such as for example changing norms and values, can lead to a change in R&D agendas.

Function 4: Guidance of the search

The activities within the innovation system that can positively affect the visibility and clarity of specific needs among technology users fall under system function: 'Guidance of the search', one example being the announcement of the government goal to aim for a certain percentage of renewable energy in a future year. This event gives a certain degree of legitimacy to the development of sustainable energy technologies and stimulates the allocation of resources for this particular development. Expectations are also included since expectations can occasionally converge on a specific topic and generate momentum for change in a specific direction.

Function 5: Market formation

New technologies often have difficulties competing with embedded technologies, therefore it is important to create protected spaces for new technologies. One possibility is the formation of temporary niche markets for specific applications of the technology (Schot, Hoogma, and Elzen 1994). Another possibility is to create a temporary competitive advantage by favourable tax regimes or minimal consumption quotas.

Function 6: Resource mobilisation

Resources in terms of both finance and human capital are necessary as basic input to all the activities within the innovation system. Specifically for biomass technologies, the abundant availability of the biomass resource itself is also an underlying factor that determines the success or failure of a project.

Function 7: Advocacy coalition (creation of legitimacy/counteract resistance of change)

In order for it to develop well a new technology must become part of an incumbent regime, or even overthrow it. Parties with vested interests will often oppose this force of 'creative destruction'. In such a case, advocacy coalitions can function as a catalyst; they put a new technology on the agenda (F3), lobby for resources (F6), favourable tax regimes (F5) and by doing so create legitimacy for a new 'technological trajectory' (Sabatier 1988; Sabatier and Jenkinssmith 1988; Sabatier 1998). If successful, advocacy coalitions grow in terms of size and influence and may become powerful enough to brisk up the spirit of creative destruction.

It is important that each individual system function is served. However, the growth of a TIS is claimed to be related to the interaction dynamics between the system functions. Positive interactions between system functions could lead to *virtuous cycles* that accelerate the growth of an innovation system and lead to the diffusion of a new technology (see Figure 1, representing possible virtuous cycles).

Using empirical data as the basis the interactions between the system functions can be assessed, whether a positive or a negative cycle takes place. Because we have defined seven system functions, many interactions are possible. However, the number of starting points is likely to be much smaller. We expect to observe certain patterns of interaction more often than others. One example of a virtuous cycle we expect to see regularly in the field of sustainable technology development is the following. The virtuous cycle starts with Function 4: 'Guidance of the search'. In this case, societal problems are identified and government goals are set to limit environmental damage. These goals legitimise the mobilisation of resources to finance R&D projects in search

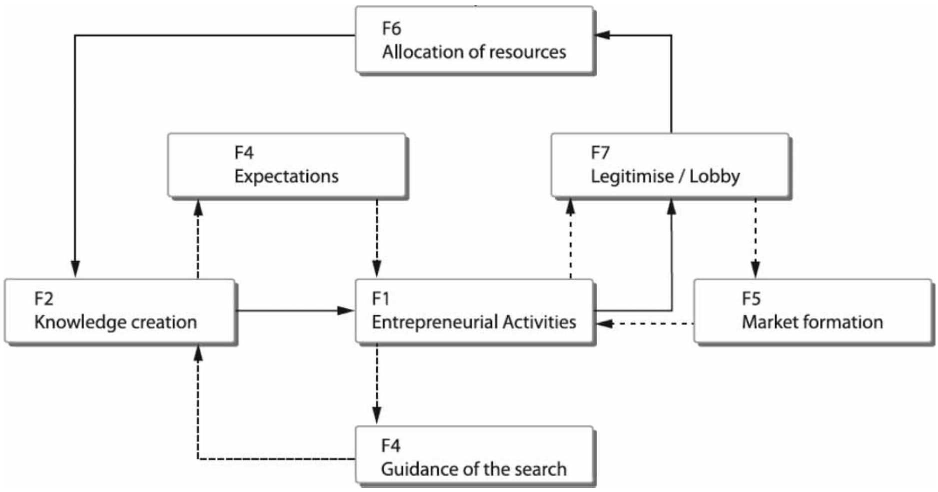

Figure 1. Overview of possible reinforcing cycles within an IS.

of solutions (Function 6), which, in turn, is likely to lead to knowledge development (Function 2) and increased expectations about technological options. Another virtuous circle that we expect to occur regularly starts with entrepreneurs lobbying for better economic conditions in order to make further technology development possible (Function 7). They may either lobby for more resources to perform R&D, leading to higher expectations, or they may lobby for market formation, because very often a level playing field is not present. If this lobby leads to the creation of markets (Function 5), an entrepreneurial activities boost is expected (Function 1), leading to more knowledge formation (Function 2), more experimentation (Function 1), increased lobbying (Function 7) for even better conditions, and high expectations guiding further research (Function 4). Many other combinations are possible; the causality is bound to be very complex, for example, when different system functions enhance each other.

Vicious cycles are also possible. These are cycles in which a negative function fulfilment leads to reduced activities related to other system functions, thereby slowing down or even stopping progress. For example, if the expectations of a technology are high (F4) but the practical results are disappointing, a collective disillusionment in the technology (−F7) may rise and thus bring an end to new projects being set up (−F1). This can reduce the amount of activity for knowledge development (F2) and lessen the availability of resources (−F6). Another possible vicious cycle is the lack of consistent government guidance (−F4), resulting in the absence of a market (−F5), and consequently there is no incentive for entrepreneurs to set up projects (−F1). In turn, this can lead to less support and lobbying (−F7) for better institutional conditions (−F4) and so forth, until the system eventually collapses. By analysing a successful case we hope to gain insight into the build-up of virtuous cycles that lead to the successful diffusion of emerging technologies.

3. Methodology

3.1. *Historical event analysis*

The method we use to map functional patterns is inspired by the 'Historical event analysis' as used by Van de Ven and colleagues (Van de Ven et al. 1999; Poole et al. 2000). Stemming from organisational theory, their usual focus is on firm and firm networks; in our case, the analysis is applied to the level of technological innovation systems.

Basically, our approach consists of retrieving a wide range of activities using a variety of sources related to the development and diffusion of the technology studied; the data for this paper were collected from Lexus Nexus,[2] newspapers, magazines, reports and websites. The data will be used to reconstruct the chronological development of biomass digestion technology in Germany in the period 1990–2005. The events are stored in a database, classified and systematically allocated to specific system functions. Each event category is allocated to one system function using a classification system (see Table 1) in which specific event categories are allocated to specific system functions. During this procedure, the classification system was developed in an inductive and iterative fashion. The classification system and event categories are verified by another researcher

Table 1. Operationalisation of system functions.

System functions	Event category	Sign/value
Function 1: Entrepreneurial Activities	Project started Contractors provide turn-key technology	+1
	Project stopped Lack of contractors	−1
Function 2: Knowledge Development	Desktop/Assessment/Feasibility studies, reports	+1
Function 3: Knowledge Diffusion	Conferences	+1
Function 4: Guidance on the Search	General: *Positive* expectations of renewable energy; Regulations by government on renewable energy Specific: *Positive* expectations on biomass digestion; Regulations by government on biomass digestion	+1
	General: *Negative* expectations on renewable energy; Regulations by government on renewable energy Specific: *Negative* expectations on biomass digestion; Regulations by government on biomass digestion	−1
Function 5: Market Formation	Feed-in rates, environmental standards, green labels	+1
	Expressed lack of feed-in rates, lack of environmental standards, green labels	−1
Function 6: Resources Mobilisation	Subsidies, Investments Biomass allocated to project	+1
	Expressed lack of subsidies, investments Expressed lack of biomass streams allocated to project	−1
Function 7: Advocacy Coalition	Lobby by actors to improve technical, institutional and financial conditions for biomass digestion	+1
	Expressed lack of lobby by actors; Lobby for other technology that competes with biomass digestion	−1

to improve reliability. Any differences in the coding results of the researchers are analysed and resolved.

Table 1 shows the allocation system of how events reported in literature are allocated to the system functions. We indicate whether the events are labelled as positive or negative.

The contribution of an event to the fulfilment of a system function may differ considerably from event to event. Some events have a positive contribution to the diffusion of the technology, while others contribute negatively as an expression of disappointment for instance, or the opposition of an important political group. The positive and negative events are included in the story line so as to yield specific insights into controversies emerging around the analysed technology.

4. The case of German biomass digestion

4.1. *Technological background*

Anaerobic digestion is a low-temperature biochemical process, through which a combustible gas – biogas – can be produced from biomass feedstock. Biogas is a mixture of carbon dioxide (CO_2) and methane (CH_4) which can be used to generate heat and/or electricity via secondary conversion technologies such as gas engines and turbines. Most biomass digestion plants operate according to the principle of 'wet digestion'[3] in which the basic substrates are cow and pig manure. Depending on the region, other manure and poultry excrements are digested as well, but in much lower quantities.[4] In more than 90% of the plants, co-substrates are also co-digested, such as energy crops, harvest surplus, verge grass, fat, food residues, and local organic household waste. The added share of co-substrates varies, on average, between 20 and 50% (E&M 2002; Berenz 2003). Co-digestion is allowed as long as the criteria of the 'Biomass ordinance' are respected. In 2001, the 'Ordinance on generation of electricity from biomass'[5] ('Biomass ordinance') was published by the 'Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety'[6] (BMU), defining which substances fall under biomass, which technologies should be used for the conversion of biomass to electricity, and which environmental standards need to be observed (Janzing 2001b).

There are two types of biomass digestion plants in Germany: the decentralised, farm-scale plants (EHA[7]) and the centralised, large-scale plants (BGA[8]). EHAs with a capacity of less than 70 kW dominate in the South and Southwest of Germany whereas in the North and in the Eastern federal states,[9] the BGAs can be found, with an average capacity of 200 kW (E&M 2002; Umbach-Daniel 2002). The differences in agricultural structure[10] are a result of the high cattle density in the South compared to the North (Berenz 2003). As a result, in the South, EHAs are set up on farms where manure and agricultural surplus from the respective farms are co-digested and electricity and heat are provided to the farm buildings. Any electricity surplus is then fed into the grid (Janzing 2001a,b,c; Muehlstein 2001b; Börnecke 2004; Kuhr 2005). In the North, the BGAs are a cooperation of several agricultural or energy supply firms, where more than two farmers provide the biomass feedstock (Umbach-Daniel 2002). Farmers and others deliver the biomass (i.e. organic waste from industry or communities) to the BGA where biomass digestion production and utilisation is centralised and the electricity produced is fed into the electricity grid (Umbach-Daniel 2002).

In this paper the diffusion of the EHAs will be analysed because this diffusion is very successful. See Umbach-Daniel (2002) for an analysis of the factors underlying the low diffusion of BGA type plants.

4.2. *Historical overview of the evolution of German biomass digestion, 1990–2006*

In the following section the evolution of the Biomass Digestion Innovation System will be reconstructed, reference being made to the various system functions as F1, F2, F3 etc., according to Table 1. The description will be subdivided into different periods. The end of each period is chosen on the basis of a change in key activities; therefore, not all periods are equal in length. At the end of each period the sequence of the activities will be analysed on the basis of the system functions fulfilled and on whether virtuous or vicious cycles occurred.

1990–1997: From the do-it-yourself (DIY) era to turnkey technology

Between 1980 and 1990 pioneers set up about 15 pilot farm-scale plants (mainly situated in the South) (Schultz 2001; Berenz 2003; StMLU 2003). However not until the early 1990s do more activities occur that are driven by the introduction of the '*Electricity Feed Act*'[11] (EFA) for renewable energy and the taxing of fossil fuels[12] (Metzger 1997; Urbach 1997; Berenz 2005). As a result of the introduction of these regulations the expectations among engineers and entrepreneurs have increased that biomass digestion technology could become a promising energy conversion technology for electricity production (F4) (Guelzow 2000; Bach 2003). In order to realise these expectations the 'German Biogas Association' (GBA)[13] was founded in 1992 (Fachverband-Biogas 2005). The GBA fulfils two important system functions, i.e. knowledge diffusion (F3) and advocacy coalition (F7), by bringing together different parties involved in the setting up of biomass digestion projects, putting biomass digestion technology on the political agenda (F7), and supporting the exchange of experience and knowledge in the biomass digestion sectors (F3) (FachverbandBiogas 2005; Schmack 2006). This increasing support of, and interest in, biomass digestion technology incites the setting up of several other engineering companies in 1995, specialising in the development, planning, and construction of 'ready-to-use' biomass digestion plants, such as Schmack Biogas AG, Farmatic Anlagenbau GmbH, and Biogas Nord (F1) (Koepke 1999; Bach 2003; FachverbandBiogas 2005). The setting up of such companies (F1) helps to change the image of the biomass digestion sector from 'do-it-yourself' and 'eco-fundamentalism' towards a professional, turn-key technology in the period 1997–1999 (F6, F7) (Stern 1999). In addition, the 'Agency for Renewable Energy' (FNR) is set up as project leader of the 'Federal Ministry for Food, Agriculture, and Forestry' (BML) to support and supervise research on biogas (F4), initiate workshops for project members (F3) and to put the obtained results at the disposal of all interested parties (F3) (Guelzow 2000; Bach 2003). As a result, biomass digestion technology is quickly seen as a serious candidate for renewable energy production.

To summarise the development of this period, the government guides the search by introducing the 'Electricity Feed Act' (F4). In addition, public and private agencies to lobby the diffusion of biomass digestion technology and its exposure as a renewable energy technology are set up (F7). At the same time entrepreneurs carry out research (F2) so as to provide a professional biomass digestion technology (F1). These simultaneous developments lead to several building blocs (guidance by the government, a well-organised sector and a well-functioning technology) being put in place that will provide the basis for the build up of the innovation system.

1998–2001: 'Green power'

The following years were characterised by major changes in the institutional environment, i.e. change in government, the increase of feed-in rates[14] and liberalisation of the energy market. After the elections in 1998 the governing conservative party (CDU) was replaced by a coalition of the Social Democratic Party (SPD) and the Green Party (Bündnins 90/Die Grünen) until 2005

(Red/Green Coalition) (Decker et al., 2007). This new federal government strongly supported power generation from renewable energy and in the same year the 'Electricity Feed-in Act'[15] was altered and the feed-in rates increased (F4) (Solarenergie-Foerderverein 1999). The government expected that by increasing the feed-in rates energy companies would produce more renewable energy and that, by liberalising the market, the consumer would choose those renewable energy sources. However, renewable energy sources are still more expensive, 15 cents/kWh compared to 9 cents/kWh, since energy companies provide cheaper energy by importing nuclear energy (Metzger 1999). Therefore, very few consumers made the switch from conventional energy to renewable energy. The electricity company 'Naturstrom AG' had high expectations of winning over some 12,000 customers by the end of 1999; however, only about 1,200 customers were actually connected (Koch 1999).

The government soon recognised that the achievement of their goals was jeopardised and the Federal Ministry of Economics and Technology[16] (BMWi) introduced a 'Market stimulation programme for renewable energy'[17] to get back on track (F4) (Hell 1999). The aim of this programme was to achieve the goal set by the Federal Government to double the share of renewable energy in the total energy supply until 2010 (Hell 1999).

The combination of the programme (F4) and the alternation of feed-in rates (F5) resulted in the biomass digestion sector continuing to grow; some 150 biomass digestion plants were built in 1998 and the construction of yet another 150 plants was predicted for 1999 (F1) (Bischof 1999; Stern 1999). Nonetheless, engineering companies such as Schmack hoped for even higher feed-in rates for small-scale plants (about 12.5 eurocents) and have high expectations (F4) regarding the introduction of a new regulation in sight (Koepke 1999).

Again, the government recognises that liberalisation of the energy market does not have the desired effect of increasing the share of renewable energy and therefore the decision is taken to replace the 'Electricity Feed Act' (1991/1998) with one of the most important regulations, the '*Act on granting priority to renewable energy*', also known as the 'Act on Sale of Electricity to the Grid'[18] ('Act') (F4) (Janzing 1999b; BMU 2000). It is believed that the goal of doubling the share of electricity produced by renewable energy by 2010 can only be achieved if renewable energy producers are guaranteed a fair, long-term remuneration and a reliable basis for investments (Janzing 1999b). The new rates provide improved perspectives for the agriculture and forestry sector thanks to the higher rates (10 cents/kWh) compared to the previous rate of 7.5 cents/kWh, and no distinction is made with respect to plant size (F5). Furthermore, these rates will remain the same for the next twenty years, with no limit to the amount of electricity to be fed in (see Table 2 for an overview of the rates per plant size compared to the previous rate) (Solarenergie-Foerderverein 1999; Haas 2000; Janzing 2000a). Here the government decided on its own account to alter the institutional setting in order to ensure that their targets will be achieved.

Dr Gerhard Rech, head of the Department of Renewable Raw Materials and Energy of the 'Federal Ministry for Food, Agriculture, and Forestry' (BML),[19] expects the feed-in of electricity from the agricultural sector to double as a result of the new remuneration rates (F4) (Haas 2000). As additional support, the BML ensures farmers that they can cultivate energy crops on 'fallow land' without losing the subsidy for keeping the land fallow (F4) (Haas 2000). On top of that, the FNR agency, with support of the BML, made a guideline report[20] available for the successful implementation of bioenergy projects (F4) (Guelzow 2000).

The anticipated boost in the biomass digestion sector was observed shortly after. In 2000, about 200 plants are set up, and a further 200 in 2001 (F1). Figure 2 represents the diffusion of biomass digestion technology (FachverbandBiogas 2005). In fact, Ulrich Schmack, of Schmack Biogas GmbH, expects that biomass is the most important energy source for an energy transition, in

Table 2. Overview of rates per size of biomass digestion plant (BMU 2000).

Electricity Feed Act (1991/1998)	Remunerative arrangement (Act 2000)	Installed electrical capacity
7.5 cents/kWh	10.23 cent/kWh	Up to 500 kW
	9.21 cent/kWh	Up to 5 MW
	8.70 cent/kWh	5–20 MW
		From 1 January 2002 onward, the remuneration would be reduced by 1% for each newly built plant

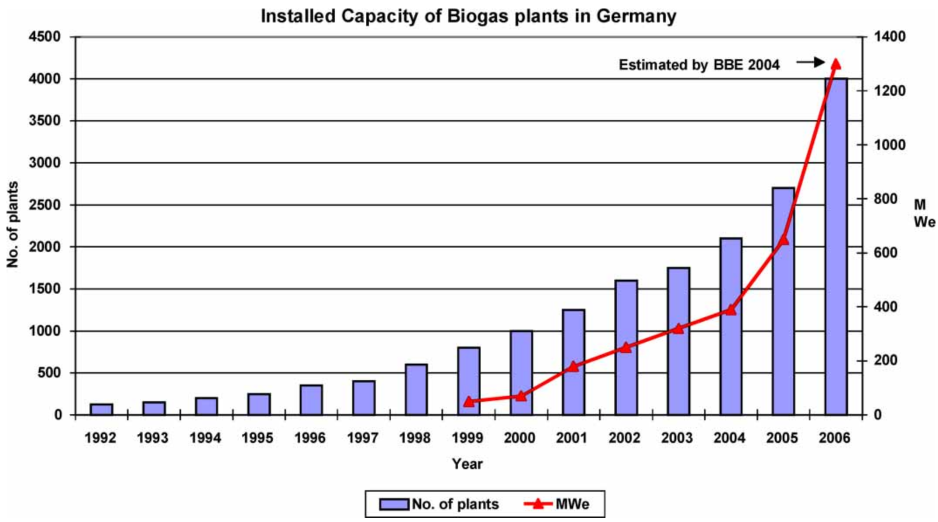

Figure 2. Installed capacity of biomass digestion plants in Germany (FachverbandBiogas 2005).

which 20–25% of the national energy demand could be covered by biomass, and that over several years each community will have its own biogas plants (F4) (Janzing 2001a).

However, the majority of those plants are still located in the Southern part of Germany, Bavaria and Swabia, which makes the other Federal States developing countries in comparison (Köpke 2001a). In order to increase the diffusion of biogas plants in other states as well, the Green Party wrote a proposal with the Social Democratic Party (SPD), to start a 'Federal State Biomass Offensive', the goal of which was to inform farmers about the potential and the advantages of biogas plants (F4) (Köpke 2001a). Here the government realised that not only were the allocation of resources (F6) and market formation (F5) important but that the fulfilment of other system functions, such as in this case, knowledge diffusion (F3), was also important in order to increase the diffusion of biomass digestion in other regions as well.

In addition to the profitable feed-in rates, the '*Ordinance on Generation of Electricity from Biomass*' ('Ordinance')[21] was introduced with the aim to optimalise the availability of biomass and waste streams (F4) (Preuss 2001a; Janzing 2002). The Ordinance defines which substances fall under biomass, which technologies are to be used for the conversion of biomass to electricity, and which environmental standards have to be complied with (Janzing 2001b). By prescribing which biomass is allowed a great deal of the uncertainty among entrepreneurs and farmers is removed. Again the government provided guidance (F4), not by providing financial means (F6) but by introducing guidelines. In order to ensure the flawlessness of the Ordinance, a scientific monitoring of two and a half years was carried out, where different biomass streams were assessed (BMU 2000; E&M 2002). This combination of the Act and the Ordinance formed the very basis of an increasing expansion of electricity production from biomass digestion in Germany, with the expected setting up of another 600 biomass digestion plants with a total capacity of 75MW between 2001 and 2002 (Kueffner 2001). Given these positive expectations, Da Costa Gomez, managing director of the GBA, estimates:

> … biomass digestion technology to cover up to 11% of the electricity supply in Germany in 2010 … and … biomass digestion production to be a second income and employment pillar for farmers, since the profits of biomass digestion plants are guaranteed for the next 20 years, due to the improved feed-in rates and guaranteed stability of 20 years; in addition, the image of the agricultural sector would be improved if farmers were looked upon as energy providers. (Schultz 2001)

Also in this period, guidance by the government (F4) to increase the share of renewable energy, by increasing the feed-in tariffs (F5) but also by promoting knowledge diffusion (F3) and aligning institutional conditions (F4), acts as the starting point for a virtuous cycle to occur. As the government decides to increase the feed-in rates a market will be created (F5) which will trigger farmers to use biomass digestion technology as a second income source and more biogas plants will be constructed (F1). As more plants are constructed more biomass will be needed[22] and the 'Ordinance' that allows co-digestion[23] will be introduced, thereby increasing the biogas yield, making biomass digestion more profitable and attracting more entrepreneurs and farmers to jump onto this 'bandwagon' (F1). This sequence of events shows that the system functions interact positively with each other, leading to a virtuous cycle.

2002–2003: The reverse side of the medal

At this point in time all seemed to be going well for the biomass digestion sector. The technology was seen as a profitable renewable energy technology and the institutional conditions (higher feed-in rates of the EEG) were aligned with the needs of the entrepreneurs.

However, in 2002, without further notice, Minister Müller of the BMWi announced a cutback from €150 million to €86 million of the investment support for biomass digestion plants within the 'Market stimulation programme' (−F6) (Schultz 2001). As a result, the construction of plants under 200 kW was economically unprofitable and several farmers stopped their initiatives (−F1) (Schultz 2001; Muehlstein 2001a). This reduction of financial resources (−F6), causing the non-profitability of small and medium sized biomass digestion plants using only 'natural' biomass[24] (−F1) (Pecka 2003e), resulted in a decreased growth of the biomass digestion sector. In the first half of 2003 only 30 plants were set up as opposed to the 75 in the previous year (Pecka 2003e). Furthermore, many projects were now on hold and entrepreneurs could not set up any new projects, as argued by the vice-president of the GBA, Markus Ott:

> … another 200 projects are ready to be set up but are on hold, waiting for a clear sign from Berlin. In the current situation, entrepreneurs of biomass digestion plants can only do as much as retrofitting or expansion work…. (Pecka 2003e)

In an attempt to boost entrepreneurial activities the Green Party[25] started an initiative (F4) to better inform farmers about the advantages of and profits from biomass digestion. Furthermore, a support programme[26] for biomass digestion plants was set up (F4) (Köpke 2001a; E&M 2002; Gruber 2005). Additionally, to compensate for the previous cut back on research money in the Market Stimulation Programme, the Federal Commission[27] agreed 'to increase the budget[28] for the programme from €150 million to €200 million for 2002' (F6) (Muehlstein 2001a).

To summarise, the cut back of the budget (−F4) triggered several negative activities, such as the discontinuation of projects (−F1) and the reduction of financial resources (−F6). However, thanks to the increased legitimacy (F7) and fast action of the Federal Commission (F4), the worst was avoided, with the result that new financial resources (F6) were made available for the continuation of projects (F1).

2004–2006: The breakthrough

The previous dip was overcome when, in 2003, preparations for the amendment of the Act under the leadership of Jürgen Trittin, Minister for Environment, started to develop (F4). The Green Party organised a conference to give all interested parties the opportunity to influence the amendment (F4) (Gammelin 2003). The aim of the conference was to counteract the opponents of renewable energy with constructive work, instead of getting caught up in polemics (F7) (Gammelin 2003). Following this conference, the Federal Ministry for the Environment (BMU) accepted the concept for the amendment of the Act by the GBA (F4) (Pecka 2003e). This concept was in agreement with the requests of the Federal Bioenergy Union[29] and the German Farmers Union,[30] and the following amendments were proposed:

> Rates higher than 10 cents/kWh; additional compensation of 2.5 cents/kWh for the use of 'traditional' products for plants with an electrical capacity; compensation of 12,5 cent/kWh for plants of 75 kW and 11.5 cents/kWh for 200 kW plants; facilitation of the complicated and lengthy permit regulations, since many regulations[31] contradict each other, resulting in the delayed set up of biomass digestion plants. (Pecka 2003e)

Finally, on 1 August 2004, the *amendment of the Act* (*Renewable Energy Source Act – EEG*[32]) entered into force, with the aim:

> … to facilitate a sustainable development of energy supply, particularly for the sake of protecting our climate, nature, and the environment, to reduce the costs of energy supply to the national economy … and … to contribute to the increase in the percentage of renewable energy sources in power supply to at least 12.5% by 2010 and to at least 20% by 2020. (BMU 2004)

The new EEG version provided additional fees (bonuses) that can be used in combination if the electricity is produced exclusively from self-regenerating raw materials,[33] combined heat-power, or if the biomass is converted using innovative technologies (e.g. thermal chemical gasification, fuel cells, gas turbines, etc.) (F4) (BMU 2004). Table 3 provides an overview of the old and new fees for electricity produced by plants with a capacity up to and including 20MW, exclusively using biomass.

The most agreeable change was the increased bonus from 2.5 to 6 cents/kWh for plants up to 500 kW, using self-regenerating raw materials as requested by the GBA, the Federal Bioenergy Union and the German Farmers Union in 2003 (Pecka 2004b). In addition, a bonus of 4 cents/kWh would be given to plants up to 5 MW when using raw materials[34] (Pecka 2004b). The expectations were very high thanks to the improved rates. For 2004, the construction of another 500 plants, each with an average capacity of 330 kW, was expected (Pecka 2004b). Dr Da Costa Gomes, GBA

Table 3. Overview of old and new fees of the Act.

Installation capacity	Electricity Feed Act (1991/1998)	Fee paid (ct/kWh) (EEG 2000)	Bonus for using renewable raw materials (EEG 2000)	Fee paid (ct/kWh) (EEG 2004)	Bonus for using renewable raw materials (EEG 2004)
Up to 150 kW	7.5 cents/kWh			11.50	
50–500 kW		10.23	2.50	9.90	6.00
500 kW–5 MW		9.21		8.90	4.00
5–20 MW		8.70		8.40	
KWK bonus (FNR 2005)				2.00	
Technology bonus[a] (FNR 2005)				2.00	

As of 1 January 2002, the remuneration will be reduced by 1% for each newly built plant (EEG 2000).
From the amended Act, the new digression rate will change from 1% to 1.5% (EEG 2004).
[a]A supplementary payment of 2 cents/kWh is added when innovative technologies such as fuel cells, gas turbines, ORC (organic Rankine cycle) installations (in particular Kalina cycle or Stirling motors) are used.

even expected that: '…the demand for biomass digestion installations would be higher than the capacity of biomass digestion technology suppliers …' (Pecka 2004b; Pecka 2005a).

Once again, the expectations were fulfilled with the setting up of another 600 plants, bringing the total number of plants in 2005 to 2700 with a total capacity of 650 MW (Keck 2004; Pecka 2005a). The managing director of GBA expected that from now on energy companies would invest in biomass digestion plants as well thanks to the improved conditions, such as the higher rates and facilitated conditions for feed-in, transfer and distribution of electricity as a result of the amendment of the Act (F4) (Shafy 2004; Pecka 2005a).

Also the EU Commission confirmed the success of the EEG. It turned out to be the most efficient and convenient method to support the development and diffusion of renewable energy, as can be seen from the high diffusion of biogas plants, but it also provided 120,000 jobs, a turnover of €6 billion and a reduction of 35 million tonnes CO_2-equivalent in 2001 (BMU 2002; COM 2005; Pressedienst 2005).

In this period, the trigger for the long-awaited breakthrough of biomass digestion was provided through the introduction of the EEG by the Red/Green Coalition (F4). The EEG turned out to fulfil all expectations due to the government aligning to the requests of the sector and the sector providing clear demands and wishes (F7). The higher feed-in rates provide a market for biomass digestion technology (F5) and this attracts more entrepreneurs and farmers to set up biogas plants (F1). At last, biomass digestion is propelled from a development phase into a diffusion phase.

5. Conclusion

The research question of this paper is: *Can the successful diffusion of biomass digestion in Germany be explained by a well-functioning innovation system*?

First, with respect to the method used, it can be said that the system functions approach proved to be a useful tool for systematically analysing and structuring the empirical data. It allowed the identification and analysis of the reasons for the success of biomass digestion in Germany. All the events that were collected could be allocated to one of the system functions. This backs the assumption, as has been shown in several other studies (Suurs and Hekkert 2005; Negro 2007; Negro, Hekkert, and Smits 2007; Negro, Suurs et al. 2008), that the system function list proposed by Hekkert et al. (2007) is relevant and that no system function is superfluous, nor that any system functions are missing.

Second, the empirical conclusions are the following. The dynamic analysis of biomass digestion in Germany shows that positive functional patterns occur. All system functions are present, fulfilled and interact with each other, leading to the build-up of a well-functioning innovation system. As a result, the system gains enough critical mass to overcome technical problems and institutional changes, such as liberalisation of the energy market. Furthermore, as the system functions interact with each other, they reinforce each other and incite other system functions to be fulfilled as well. The main trigger behind the build-up of a well-functioning innovation system is a highly successful government that focused on many system functions, starting with guidance (F4), creation of legitimacy (F7), followed by market formation (F5) and resource mobilisation (F6). In addition, knowledge development (F2) and diffusion (F3) were also stimulated by the government by setting up research programmes and agencies. On top of that, the activities of the government (increase of feed-in rates) were well aligned with the needs of the biogas sector. This shows that the government played the role of a system builder, where other aspects than only financial ones, were fulfilled.

Then again, the build-up of an innovation system cannot only occur through one single actor, but through the interplay of several actors within the biogas innovation system. In fact other actors, such as entrepreneurs, farmers and engineers, performed complementary activities, such as developing turnkey technologies (F1), knowledge creation (F2), knowledge diffusion (F3), construction of biogas plants (F1) and by skilfully articulating their demands and wishes (F7). The fact that biogas advocates were well organised undoubtedly helped to convey a clear message to the government. The growth of the sector in terms of labour market empowered the sector in terms of legitimacy. This well-functioning ‘private’ part of the innovation system stimulated the government even more to align its activities to the sector’s needs so as to increase the diffusion of the technology. With the continuous support (F5, F6) and long-term guidance by the government (F4), the number of entrepreneurs increased to set up more plants (F1), leading finally to the breakthrough of biomass digestion technology.

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Notes

1. This list of system functions has to a large extent been developed in agreement with colleagues from Chalmers University (Sweden) to be applied to empirical work both in the Utrecht and the Chalmers group.
2. The Lexus Nexus™ academic news archive contains all articles that have been published from 1990 onwards. It is quite a homogeneous source that allows for quantification of the data retrieved. Relevant articles can be found by performing a keyword search. The keywords used are: Biomasse, Biomasse vergären/Vergärung and Biogas and other more specific ones to obtain more information on specific topics, i.e. Liberalisierung Energie Markt.
3. In German: Nassvergärung.

4. Biomass digestion is only profitable with 80–100 ‘cattle units’ (in German: Grossvieheinheiten); 100 cows can cover the energy need of 30 average households, where each cattle unit produces about 1.5 m^3 of biogas (Janzing 2000; FAZ 2003).
5. In German: Biomasse Verordnung (BiomasseV).
6. In German: Bundesministerium fuer Umwelt, Naturschutz und Reactor Sicherheit (BMU).
7. In German: Einzelhofanlagen (EHA).
8. In German: Biogasgemeinschaftsanlagen (BGA).
9. In German: Länder.
10. In German: Agrarstruktur.
11. In German: Energie-/Stromeinspeisegesetz (BGBI I S.2633) (passed on 7 December 1990, predecessor of the ‘Act on granting priority to renewable energy’ introduced in 2000). Public electricity utilities are obliged to feed electricity produced by renewable energy into the grid and to compensate 80% of the average price per kWh of the electricity produced by biomass (Urbach 1997).
12. In German: Mineralölsteuergesetz (MinöStG) (BGBI S. S. 2150, 2185) passed on 21 December 1992.
13. In German: Fachverband Biogas e.V (www.biogas.org).
14. Feed-in rates are rates that are paid for every kWh of electricity fed into the utility grid (BMU 2000).
15. The Feed-in Act (StrEG) was altered on 24 April 1998 by article 3 Nr 2 (BGBI 1 S. 730/734). Electricity produced by biomass and geothermal are compensated with 8.25–8.75 cents/kWh (16.5–17.5 Pf/kWh) (Metzger 1997; Solarenergie-Förderverein 1999) Nb: Conversion rate: 1 DEM = €0.511292; 1 EUR = 1.95583 DEM (http://www.xe.com/ucc/convert.cgi; 2006.02.20 10:09:29 UTC).
16. In German: Bundesministeriums für Wirtschaft und Technologie (BMWi).
17. In German: Marktanreizprogramm zu Gunsten erneuerbarer Energien. The total budget is €100 million, of which, annually, €36 million (35% of the total sum, until 2002) are reserved for biomass technologies, where biomass digestion plants could obtain €19k–153k depending on their size (Haas 2000).
18. In German: Gesetz für den Vorrang Erneuerbarer Energien, EEG, passed on 17 March 2000 by the Bundestag.
19. With the organisational decree of the Federal Chancellor from 22 January 2001, the Federal Ministry for Food, Agriculture, and Forestry (BML) was transformed into the Federal Ministry of Consumer Protection, Food, and Agriculture (BMVEL).
20. In German: Leitfaden Bioenergy.
21. In German: BiomasseVerordnung (BiomasseV), passed on 21 June 2001 by the Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety (BMU), acting in agreement with the Federal Ministries for Consumer Protection, Food, and Agriculture and for Economics and Technology, and respecting the rights of the German Bundestag.
22. In 1996 the fermentation capacity of organic waste from households was above 4 million tonnes per year in Germany. The result is that already more than half of the potential of organic waste is used in (relatively new) fermentation plants (fermentation = conversion of organic waste under aerobic conditions whereby compost is produced but no biogas is collected as an energy source). The result is that the availability of biomass streams are scarce for the digestion of organic waste and that digestion from households will be only considered if the fermentation plants need retrofitting. However, because of the recent increase of the feed-in tariffs, the aspect of profitability has shifted to digestion, and with the introduction of the ‘Ordinance’ an initiative is undertaken to optimise collection of the organic waste streams for digestion (Mueller 2001a). Thus for the time being the remaining streams are guaranteed for digestion. The aim, however, is to switch from fermentation to digestion.
23. In more than 90% of the plants, co-substrates are co-digested with manure, such as energy crops, harvest surplus, verge grass, fat, food residues, and local organic household waste. The added share of co-substrates varies, on average, between 20% and 50%. Co-digestion is allowed as long as the criteria of the ‘Biomass Ordinance’ are respected; this removes a great deal of uncertainty for the plant operators and provides increased biogas yields (E&M 2002; Berenz 2003).
24. In German: Naturbelassen, untreated biomass, i.e. agricultural surplus, energy crops, verge grass, manure. A higher energy yield is obtained when frying fat or other products from the food industry are co-digested.
25. In German: Bundestagsfraktion Buendnis 90/Die Grünen.
26. In German: ‘Rationelle Energieverwendung und Nutzung unerschöpflicher Energiequellen’ (REN-Programm). The aim is to accelerate the market introduction rate of emerging technologies, including biomass and biogas plants (Gruber 2005).
27. In German: Bundeshauptausschuss’.
28. In German: Haushaltansatz.
29. In German: Bundesverband Bioenergie, BEE.

30. In German: Deutschen Bauernverband, DBV
31. Such as federal emission regulations, construction rights, increasing security requirements, organic waste regulations, waste laws, EU-hygiene guidelines, fertiliser laws, and different state operations (Pecka 2003e).
32. In German: Energieeinspeisegesetz (EEG).
33. In German: Nachwachsende Rohstoffe (NawaRos).
34. In addition to the renewable raw material bonus, an incentive for the use of the produced heat and innovative technologies, i.e. 2 cent/kWh per new plant, is available. The CHP bonus is only available for electricity production, corresponding to the requirements of the 'CHP modernisation law'. The technology bonus would provide fewer impulses, even though some operators did profit from it. Nonetheless, in this respect the upgrading of biogas to natural gas quality could be favoured, which would stimulate the feed-in of biogas into the gas grid. However, a gas feed-in law is still out of sight in Germany (Pecka 2004b), at least until 2006 when the Green Party would launch another attempt to propose a 'Feed-in Law for Biogas' (Einspeisegesetz für Biogas) along the lines of the 'Feed-in Act for Electricity' (Gammelin 2006).

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