Identifying Typical (Dys-) Functional Interaction Patterns in the Dutch Biomass Innovation System

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1 Introduction

Innovation is increasingly being considered crucial to deal effectively with the negative side effects associated with economic growth. Influencing the direction of innovation towards more sustainable paths is high on many political agendas. Issues like global warming, the security of energy supply, local air pollution, and the negative social effects of economic growth have strongly contributed to these insights.

In recent literature, a structural re-orientation of economic activity towards sustainability has been labelled as a process of sustainable socio-technical change, industrial transformation and (socio-) technological transitions (Rohracher 2001; Rotmans et al. 2001; Geels 2002; Brown et al. 2003; Vergragt 2004; Smith et al. 2005; Kemp et al. 2007). In these contributions, the emphasis lies on the development of new modes of governance to support these processes, e.g., transition management at the level of societies and strategic niche management and socio-technical experiments at the level of specific innovation processes (Vergragt 2004; Smith et al. 2005; Kemp et al. 2007; van der Laak et al. 2007; Brown and Vergragt 2008). Due to different disciplinary backgrounds, only a limited number of insights from the field of innovation studies are being applied to this new and rapidly growing field of sustainable socio-technical change. This is remarkable, since innovation is a key process in sustainable socio-technical change and the field of innovation studies has provided a vast number of insights into the factors that explain processes of innovation and into the type of policy frameworks that support innovation.

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One of the frameworks from innovation studies that could potentially contribute to understanding sustainable technological change[1] is the innovation system approach. It has become a well-established heuristic framework in the field of innovation studies. It presents insight into the factors that explain processes of innovation (Lundvall 2002; Lundvall et al. 2002). The framework has been adopted as an analytical framework and as a guideline for science and innovation policy by numerous public organisations around the world (Commission 1996, 2002; OECD 1997, 1999a, b; Albert and Laberge 2007). Furthermore, a number of scholars have adopted the innovation system framework to study processes of socio-technical change and in many studies the focus was on emerging renewable energy technologies (Edquist and Johnson 1997; Galli and Teubal 1997; Johnson 1998; Jacobsson and Johnson 2000; Liu and White 2001; Rickne 2001; Bergek 2002; Carlsson and Jacobsson 2004; Jacobsson and Bergek 2004; Hekkert et al. 2007; Negro 2007; Negro et al. 2008a, b). More specifically, these authors have adopted the technological innovation system (TIS) approach as introduced by (Carlsson and Stankiewicz 1991). The focus of the TIS approach on the institutions and networks of agents involved in the generation, diffusion, and utilisation of a specific technology fits best with their interest in technological change compared to the national innovation systems (NIS) approach (Freeman 1987; Lundvall 1992) or the sectoral innovation (Malerba 2002) approach which both take a broader perspective.

The central connection between a TIS and socio-technical change is that emerging technologies are developed and applied within a specific TIS context. When the technology matures, the TIS also grows, due to an increasing knowledge base, new entrants, growing networks in terms of size and density, and specific institutional arrangements that are put into place. On the other hand, when a TIS grows, the rate of technological progress generally increases, which in turn leads to increased chances of success for the technology in question. Thus, the maturation of a technology and the growth of a TIS are typical examples of co-evolution; they mutually influence each other.

A novel addition to the earlier innovation system approaches is to relate innovation systems explicitly to general systems theory, an approach that has been used much more in natural sciences than in social sciences.[2] This has led to a strong focus on innovation system *functioning,* since one of the characteristics of a "system" from a general systems perspective is that it has a function, i.e. it is performing or achieving something. This was not addressed systematically in the earlier work on innovation systems. Galli and Teubal (1997) started thinking in this direction, which was followed up by Johnson (1998); Jacobsson and Johnson

[1]We use technological change and socio-technical change interchangeably. Technological change always co-evolves with changes in the social system.

[2]Edquist (2001) is strongly in favour of making this connection since it might make the innovation system framework clearer and more consistent, to serve as a basis for generating hypotheses about specific variables within innovation systems.

(2000); Liu and White (2001); and Rickne (2001). The primary goal of an innovation system is to contribute to the development and diffusion of innovations. The novelty of the work by the authors above is that they reflected on different sub-functions, which are considered to be important for an innovation system to develop and grow and, thereby, to increase the success chances of the emerging technology. In this article, when we use the term system function, we refer to these sub-functions instead of the goal of an innovation system.

The TIS framework conceptualises the energy transition process as a building up process of different TIS. A TIS is the structure surrounding a new technology. This structure consists of actors, institutions (rules of the game) and relations between them. Analyses showed that this structure has a great influence on the success and failure of new technologies. The strong point of the TIS framework is that it conceptualises the growth process of emerging TIS and thereby sheds light on the dynamics of transition paths. Based on a large number of historical case studies, it became clear that a number of key processes are crucial in the construction process of emerging TIS (Hekkert et al. 2007; Negro et al. 2007; Bergek et al. 2008b; Negro et al. 2008b; Hekkert and Negro 2009; Suurs and Hekkert 2009b).

These system functions are:

1. Entrepreneurial activities
2. Knowledge development
3. Knowledge exchange
4. Guidance of the search
5. Market formation
6. Resource allocation
7. Counteracting resistance to change.

These system functions provide handholds for policymakers and other stakeholders to accelerate transition processes (Bergek et al. 2008a). We have empirically shown that when these system functions are well developed, they set in motion a range of positive feedback mechanisms that accelerate innovation system growth (Hekkert and Negro 2009). These are labelled “motors of change” (Suurs and Hekkert 2009b).

This paper compares several biomass innovation systems in order to identify typical patterns of interactions that lead to virtuous or vicious cycles and thereby trigger or hamper the development of the respective innovation systems.

This paper is structured as follows. The theory and concepts used, such as the innovation system and system functions approach, are further described in Sect. 2. A short overview of the process method is described in Sect. 3. Section 4 summarises the findings from our earlier case studies on technological innovation system dynamic, such as biomass digestion in the Netherlands (Negro et al. 2007) and Germany (Negro and Hekkert 2008), biomass gasification in the Netherlands (Negro et al. 2008b), and biomass combustion in the Netherlands (Negro et al. 2008a). In Sect. 5 we present a cross-case analysis by combining the insights from the case studies. Section 6 concludes and discusses limitations.

2 Innovation Systems and System Functions

There are several definitions of innovation systems mentioned in the literature, which all have the same scope and are derived from one of the first definitions (Freeman 1987):

> . . .systems of innovation are networks of institutions, public or private, whose activities and interactions initiate, import, modify, and diffuse new technologies

Usually, when innovation systems are studied at a national level, the dynamics are difficult to map, due to the vast number of agents, relations, and institutions. Therefore, many authors who study and compare national innovation systems (NIS) focus on their structure. Typical indicators to assess the structure of the NIS are R&D efforts, qualities of educational systems, university-industry collaborations, and the availability of venture capital. Thus, most empirical studies of innovation systems do not focus on mapping the emergence of innovation systems and their dynamics (Hekkert et al. 2007).

However, in order to understand technological change, insights into how the innovation system around a new technology is structured are needed. Thus insights into the dynamics of the innovation system are necessary. Fortunately, the number of agents, networks, and relevant institutions in a technological innovation system (TIS) are generally much smaller than in a national innovation system, which reduces the complexity. This is especially the case when an emerging TIS is being studied. Generally, an emerging innovation system consists of a relatively small number of agents and only a small number of institutions are aligned with the needs of the new technology. Thus, by applying the TIS approach, it becomes possible to study dynamics and to come to a better understanding of what really takes place within innovation systems (Hekkert et al. 2007). According to Carlsson and Stankiewicz (1991) (p. 94), a TIS is defined 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 system for each technology and that each system is unique in its ability to develop and diffuse a new technology (Jacobsson and Johnson 2000). A TIS that functions well is a requirement for the technology in question to be developed and widely diffused. The question remains, however, what determines whether or not a TIS functions well, other than defining success by the end result, i.e. a high level of technological diffusion?

Edquist states that “the main function – or the ‘overall function’ of an innovation system is to pursue innovation processes, i.e., to develop, diffuse and use innovations” (Edquist 2004) (p. 190). In order to determine whether a TIS functions well or not, the factors that influence the overall function – the development, diffusion, and use of innovation – need to be identified. Jacobsson and Johnson (2000) developed the concept of system functions, where a system function is defined as “. . .a contribution of a component or a set of components to a system’s performance”. 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 2000). The functional pattern is mapped by studying the dynamics of each function separately as well as the interactions between the functions. The system functions are related to the character of, and the interaction between, the components of an innovation system, i.e. agents (e.g. firms and other organisations), networks, and institutions, either specific to one TIS or "shared" between a number of different systems (Edquist 2001).

Recently, a number of studies applied the system functions approach, which led to a number of system functions lists in the literature (Edquist and Johnson 1997; Galli and Teubal 1997; Johnson 1998; Jacobsson and Johnson 2000; Liu and White 2001; Rickne 2001; Bergek 2002; Carlsson and Jacobsson 2004; Jacobsson and Bergek 2004; Hekkert et al. 2007). This paper uses the recently developed list of system functions at Utrecht University (Hekkert et al. 2007; Negro 2007; Negro et al. 2008a, b) that will be applied to map the key activities in innovation systems, and to describe and explain the dynamics of a TIS.

2.1 Function 1: Entrepreneurial Activities

The existence of entrepreneurs in innovation systems is of prime importance. Without entrepreneurs, innovation would not take place and the innovation system would not even exist. The role of the entrepreneur is to transform the potential of new knowledge development, networks and markets into concrete action to generate and take advantage of business opportunities.

2.2 Function 2: Knowledge Development (Learning)

Mechanisms of learning are at the heart of any innovation process. For instance, according to Lundvall: "the most fundamental resource in the modern economy is knowledge and, accordingly, the most important process is learning" (Lundvall 1992). Therefore, R&D and knowledge development are prerequisites within the innovation system. This function encompasses "learning by searching" and "learning by doing".

2.3 Function 3: Knowledge Diffusion Through Networks

According to Carlsson and Stankiewicz (1991), the essential function of networks is to exchange information. This is important in a strict R&D setting, but especially in a heterogeneous context where R&D meets government, competitors and market. Here policy decisions (standards, long-term targets) should be consistent with the latest technological insights and, at the same time, R&D agendas are likely to be affected by changing norms and values. For example, if there is a strong focus in society on renewable energy, it is likely that a shift in R&D portfolios will occur towards a higher share of renewable energy projects. This way, network activity can be regarded as a precondition to "learning by interacting". When user-producer networks are concerned, it can also be regarded as "learning by using".

2.4 Function 4: Guidance of the Search

The activities within the innovation system that can positively affect the visibility and clarity of specific wants among technology users fall under this system function. An example is the announcement of the policy goal to aim for a certain percentage of renewable energy in a future year. This grants a certain degree of legitimacy to the development of sustainable energy technologies and stimulates the mobilisation of resources for this development. Expectations are also included, as occasionally expectations can converge on a specific topic and generate a momentum for change in a specific direction.

2.5 Function 5: Market Formation

A new technology frequently has difficulties to compete with incumbent technologies, as is often the case for sustainable 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 et al. 1994). This can be done by governments but also by other agents in the innovation system. Another possibility is to create a temporary competitive advantage by favourable tax regimes or minimal consumption quotas, activities in the sphere of public policy.

2.6 Function 6: Resource Mobilisation

Resources, both financial and human, are necessary as a 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 which can determine the success or failure of a project.

2.7 Function 7: Creation of Legitimacy/Counteracting Resistance to Change

In order to develop well, a new technology must become part of an incumbent regime, or has to even replace it. Parties with vested interests will often oppose this force of "creative destruction". In that case, advocacy coalitions can function as catalysts to create legitimacy for the new technology and to counteract resistance to change.

Both the individual fulfilment of each system function and the interaction dynamics between them are important. Positive interactions between system functions could lead to a reinforcing dynamics within the TIS, setting off *virtuous cycles, i.e. "motors of change"* that lead to the diffusion of a new technology. An example of a virtuous cycle that we expect to see regularly in the field of sustainable technology development is the following. The virtuous cycle starts with F4: guiding 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 of solutions (F6), which in turn, is likely to lead to knowledge development (F2) and increased expectations about technological options (F4). Thus, fulfilment of the individual functions is strengthened through interaction.

Vicious cycles are also possible, where a negative function fulfilment leads to reduced activities in relation to other system functions, thereby slowing down or even stopping progress.

3 Methodology

All empirical cases compared in this article used a similar method to analyse innovation system dynamics. The method used to map interaction patterns between system functions is inspired by the process method called "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, the usual focus is on innovation projects in firms and firm networks; in our case, the analysis is applied to a TIS level (Negro 2007; Negro et al. 2007).

Basically, the approach consists of retrieving as many events as possible that have taken place in the innovation system using archive data, such as newspapers, magazines, reports and professional journals. The events are stored in a database and classified into event categories. Each event category is allocated to one system function by an indicator as shown in the classification scheme. The classification scheme presented is specific to the analysis of renewable energy cases (see Table 1).

The final outcome of the process analysis is a narrative (story line) of how the development of the TIS changed over time and the role of the different system functions within this development. In the narrative, the focus is on extracting interaction patterns between system functions. We limit ourselves to a very short stylised description of each case where just the main interaction patterns between system functions are stated. For a more detailed description, we refer to the original articles (Negro et al. 2007, 2008a, b; Negro and Hekkert 2008; Suurs and Hekkert 2009a, b). Based on the content of the events and their chronological order, we are able to deduce the effect of one event on another and the order in which such events occurred. By observing reoccurring sequences of events, we are able to identify interaction patterns between system functions. We use cross-case analysis to test

Table 1 Operationalisation of System Functions

System Functions	Event categories	Sign
Function 1: Entrepreneurial Activities	Project started	+1
	Project stopped	−1
Function 2: Knowledge Development	Desktop/Assessment/Feasibility studies on the technology	+1
Function 3: Knowledge Diffusion	Workshops, Conferences	+1
Function 4: Guidance of the Search	Positive expectations of the technology; Government regulations	+1
	Negative expectations of the technology; Expressed deficit of regulations	−1
Function 5: Market Formation	Specific favourable tax regimes and environmental standards	+1
	Expressed lack of favourable tax regimes or favourable environmental standards	−1
Function 6: Resource Mobilisation	Subsidies, investments for the technology; Biomass streams allocated to the project	+1
	Expressed lack of subsidies, investments; Shortage of biomass streams allocated to project	−1
Function 7: Advocacy Coalition (Creation of Legitimacy/ Counteract Resistance of Change)	Lobby activities for the technology; Support of technology by government, industry	+1
	Lobby activities against the technology; Expressed lack of support by government, industry	−1

whether these patterns are case-specific or whether they hold more generally. Insights into these patterns are the first step towards policy recommendations regarding the governance of this set of TIS (Hekkert et al. 2007).

4 Overview of the Dynamics of Biomass Case Studies

In this section, we start with the description of one success case that shows how a virtuous cycle evolved. Then we describe two cases where virtuous and vicious cycles alternate. We end with a case where hardly any system functions interact.

4.1 Virtuous Cycles Evolving

We will start with the case of biomass digestion in Germany (Negro and Hekkert 2008). Biomass digestion is a process to produce a gaseous fuel from organic waste or manure. The main adopters in Germany are farmers who seized the opportunity to convert their excess of manure into renewable energy. The innovation system started to take off when the German government introduced the Electricity Feed-in

Act in 1990. This act states that producers of renewable energy are compensated for higher production costs compared to conventional electricity. This act guides the direction of search (F4) towards renewable energy technologies. Biomass digestion was recognised by entrepreneurs as a key technology to produce renewable energy and they started to create and diffuse knowledge (F2, F3), which led to the establishment of the first digestion plants (F1). The first trials showed however that the current legislation wa not sufficient to make a good business case for biomass digestion. Lobby activities (F7) by the German Biogas Association tried to have the institutional conditions changed. They were successful, as shortly afterwards the German government increased the feed-in rates in 1998 (F4). The level of the feed-in tariffs was such that a first market formed for biomass digestion (F5), which resulted in the construction of initially about 200 plants each year (F1), with the outcome that by the end of 2003 about 1,750 plants were standing. However, the German Biogas Association and entrepreneurs were not satisfied with the institutional conditions and undertook additional lobby activities (F7) to improve institutional conditions (F4). These requests were quickly heard by politicians, due to the presence of the Green Party in parliament, and in 2004 still higher feed-in tariffs were introduced (F4) that were guaranteed for a period of 20 years, thereby strongly reducing the uncertainties for entrepreneurs. The feed-in tariffs led to a market formation, which led to the final breakthrough for biomass digestion in Germany (F1), i.e. 2,700 plants in 2005.

This case shows that the positive interactions between six system functions explain most of the dynamics. The interplay between guidance of the search by the government, entrepreneurial activities, lobby activities to counteract resistance to change and market formation prove to be dominant. Also resource mobilisation through different subsidy programmes and knowledge development contributed to the dynamics. Only the role of knowledge diffusion was difficult to verify with the empirical data, but with hindsight, it seems fair to assume that much knowledge diffusion must have taken place between the farmers (adoptors, entrepreneurs) and the technology suppliers (entrepreneurs) to improve the technology and achieve such a high diffusion in different regions.

4.2 Virtuous and Vicious Cycles Alternating

The case described above shows mainly positive interactions between system functions. This is quite exceptional. In most cases virtuous cycles alternate with vicious cycles. This is the case of biomass co-firing in the Netherlands (Negro et al. 2008a). This implies adding biomass as a feedstock to existing coal-fired power plants. This add-on technology is quite simple compared to most other sustainable energy technologies. Moreover, in this innovation system the agents, power plants and infrastructures are already in place, as part of the incumbent system. It is interesting to see whether the dynamics and sequence of events are different compared with the other case studies where the infrastructures and important actors are not in place yet. The sequence of events started with guidance by the government, stimulating the energy companies to reduce CO_2 emissions (F4). The energy companies complied by publishing an "Environmental Action Plan". This changed the direction of search towards alternatives for coal as feedstock. Co-firing was quickly recognised as a very promising option (F2). Mr Ketting, the director of the United Electricity Producers (SEP), considered the use of large-scale electricity plants as a solution to the waste problem. By co-firing waste wood, a certain percentage of coal is replaced which reduces emissions; the waste wood is usefully processed (EnergieConsulent 1992). The government supported the ambitions of the energy companies to replace a certain percentage of coal with biomass, by providing resources (F6) and forming a market (F5) (the power producers received a subsidy for each kWh produced with biomass). This led to the quick introduction of co-firing (F1), by 2000 most of the Dutch coal plants co-fired permanently up to 5% of biomass in their plants. However, unclear and contradictory regulations (on the type of biomass and emission rules) regarding biomass co-firing (−F4), temporarily delayed the entrepreneurial activities (−F1). Lobby activities by the energy companies (F7) led to agreements with the government about new institutional conditions that are well aligned with the needs of biomass co-firing technology (F4). On top of this, the government formed an additional market for biomass co-firing by negotiating another voluntary agreement with the coal sector to reduce CO_2 emissions (F5). This was the final trigger to implement co-firing in all coal-fired power plants (F1). The prominent role of the energy companies in lobbying for favourable conditions in order to facilitate biomass co-firing in their coal plants is easily understandable when comparing the options they had to reduce CO_2 emissions. The target set by the government to reduce the CO_2 emissions by 20% in the short term and 40% in the long term can only be realised if they switch from coal to natural gas, close down the coal plant, or co-fire biomass.

The third case also showed alternating virtuous and vicious cycles, but now the vicious cycle dominated. The case of biomass gasification in the Netherlands (Negro et al. 2008b) involved advanced technology to convert biomass very efficiently into electricity and heat. The biomass gasification innovation system started with the recognition of the potential of this technology by a small group of energy specialists. Positive experiences in Finland (F3) guided these Dutch energy specialists to focus on this novel technology (F4). A waste surplus problem and the climate change issue helped to put this technology on the political agenda (F4). Several desktop and feasibility studies on biomass gasification provided very positive results (F2). Due to these positive results and the great enthusiasm of the energy experts, the expectations (F4) of the entrepreneurs and government were boosted to high levels in a short time span. As a natural consequence, subsidies were provided for research (F6) and research programmes were launched (F2). The great enthusiasm and highly strung expectations arising from positive results obtained from the research programmes, led to the setting-up of two biomass gasification projects (F1). The above showed a strong virtuous cycle during the period 1990–1998, where positive expectations (F4) strongly influenced positive system dynamics. However, the virtuous cycle was terminated after a very short period of time by one key event: the liberalisation of the energy market. Energy companies started competing for customers by means of low energy prices, which led to the termination of unproven, risky projects. A vicious cycle started to form. The lack of support from energy companies (−F4) resulted in less knowledge creation (−F2), less investments (−F6), less resources (−F6) and above all negative expectations (−F4). These negative events reinforced each other with the outcome that no activities are carried out anymore, so that the system collapsed within a couple of years. Until now, biomass gasification still has not diffused on a large scale in the Netherlands.

To summarise, the case studies described above show that the interactions between system functions lead to the (temporal) construction or deconstruction of emerging innovation systems. Virtuous cycles occur when several system functions are fulfilled, interact and reinforce each other. The question remains whether it is possible to have an innovation system where different functions are fulfilled, but where no or only limited interactions take place. What type of dynamics follows from such a lack of interaction?

4.3 System Dynamics with Limited Interaction Between System Functions

To illustrate a dynamics with limited interaction, we turn to the case of biomass digestion in the Netherlands (Negro et al. 2007), which stands in sharp contrast to the successful development of this technology in Germany (see Sect. 4.1). Two observations stand out in this case. First, an irregular functional pattern is observed, as positive and negative system functions seem to take alternative turns every so many years. Second, during most periods only a limited number of system functions are fulfilled.

In the early emergent period of the biomass digestion innovation system (1974–1987) only the system functions knowledge development (F2) and entrepreneurial activities (F1) occur, as several pilot plants were set up as a solution to the manure surplus problem (F4). However, no other system functions were triggered. In the following years, as the manure surplus problem remained unsolved, negative guidance against biomass digestion (−F4) severely hindered market formation (−F5) and investments (−F6). Surprisingly, very little lobby activities occurred (−F7). The biomass digestion entrepreneurs seemed not to be very well organised. Only in 1989 did a cautious build-up of system functions occur, when guidance (F4) due to a waste surplus, where biomass digestion seemed to be a potential solution, stimulated the knowledge creation and diffusion (F2 and F3) of biomass digestion, resulting in the establishment of several plants (F1), i.e. seven plants in 1992. However, system functions, such as market formation (−F5) and resource mobilisation (−F6) remained unfulfilled. Lobby activities were also too scarce to improve institutional conditions for digestion. One of the institutional barriers to manure digestion was that it was not allowed to add other biomass feedstock to the digester, a process referred to as co-digestion. If this were allowed, the biogas output of a digester and thereby also the profitability of the plant could be greatly increased.

In 1995, the positive guidance turned into negative guidance (−F4), as biomass digestion was not recognised by the Dutch government as a renewable energy technology. Where the German entrepreneurs were able to show the German government that digestion was a functioning renewable energy technology that deserved support, the Dutch digestion sector did not manage this. No additional resources were therefore made available (−F6), forcing several plants to shut down (−F1). In 2003, the Dutch government aimed to increase the share of green electricity (F4) and introduced a feed-in tariff system (F5). Due to this change in institutional conditions, agents of the biomass digestion sector saw an opportunity to profit from this market formation (F5) and this time started a successful lobby to allow co-digestion and to put biomass digestion as a renewable energy technology onto the political agenda (F7). Finally, an increase of biomass digestion plants occurred between 2004 and 2006 (F1).

To summarise, between 1974 and 2003 no continuous build-up of system functions occurred. Some system functions were fulfilled, but they did not mutually interact to reinforce each other and trigger other system functions. This led to a scattered functional pattern that led to an innovation system that was essentially based on "muddling through", resulting in a very low diffusion rate of the technology in question. However, it still provides a basis for virtuous cycles at a much later stage when the institutional conditions have changed.

5 Identifying Typical Interaction Patterns

5.1 The Importance of System Functions

Before identifying typical interaction patterns, a general understanding of the fulfilment of the individual system functions is needed:

- Entrepreneurial activities (F1) are a prime indicator of whether an innovation system is progressing or not. First, we observed that it is a very good indicator of technology diffusion. In most cases, technology diffusion developed in line with entrepreneurial action. Second, entrepreneurial activities proved to be a central function that connects other system functions and thereby adds to the occurrence of virtuous cycles. We often observed knowledge creation (F2) being followed by entrepreneurial activities and in turn entrepreneurial activities triggering many other system functions.
- Knowledge development (F2) is also important in all cases. This is not surprising since we studied complex technologies in the early stages of emergence where uncertainty about technological performance is high. It is only natural that much R&D is necessary to solve technological problems and create a technology with

acceptable specifications. Very often knowledge development preceded entrepreneurial activities or co-evolved with them. Thus entrepreneurs only dare to invest in new technological trajectories when a minimal knowledge base is present. When they do invest, the many technological problems they encounter are solved by additional R&D efforts. An important finding is that knowledge development needs to be defined much more broadly than just knowledge about "how a new technology functions or performs". Very often important processes of knowledge development are related to creating insights on the fit between new technologies and (1) existing business practices, and (2) existing or new regulations. Another interesting finding with respect to knowledge development is that most of these novel technologies are "new combinations" of already existing technologies, either transferred from another sector (digestion technology was already used in the 1970s for wastewater treatment) or used with a different feedstock (biomass gasification benefited from experience with coal gasification).

- The role of knowledge diffusion (F3) is much more difficult to map. We were able to measure events where knowledge diffusion is likely to take place, such as workshops, conferences and technology platforms. However, the actual knowledge diffusion processes could not be measured in this way. Also much knowledge diffusion takes place in dyadic relationships that are not reported in literature. So, many of the knowledge exchange processes do not become visible using this method. By interviewing agents in the innovation system, much more insight can be gained in the fulfilment of this function. Thus, the quantitative method is not the optimal one for measuring this function. In many trajectories we observe strong improvements in technological performance that matches the needs of technology users. Implicitly, we may assume that knowledge diffusion and even learning has taken place.
- Guidance of the search (F4) is an important system function. It stands at the base of many developments and leads to several courses of action, either positive or negative. We observed that strong guidance motivated entrepreneurs to enter a new technological field and that guidance directly influenced the amount of resources allocated to knowledge development. We also observed that a lack of guidance made the entrepreneurs reluctant to invest. Shifts in positive and negative guidance were mirrored by increasing and decreasing entrepreneurial activities. Also, most of the frustration of entrepreneurs in emerging innovation systems was due to rapid shifts in guidance and not so much to other factors, like problematical technological performance and availability of capital.
- Market formation (F5) is often addressed at an advanced state of development, but it can significantly accelerate the emergence of the TIS. For example, we observed that the success of biomass combustion in the Netherlands was directly related to fulfilling the system function "market formation". All other system functions are in place and a direct relation is visible between a well-functioning system function: market formation and system growth. Just like the guidance function, the rapid shifts in market formation had strong effects on innovation

system development. It proved to be difficult for the (Dutch) government to provide consistent policy with regard to guidance and market formation.

- Resource mobilisation (F6) turned out to be relevant in each case study. Many knowledge development projects were started via (public) allocation of resources. It proved much more difficult to mobilise resources to build and construct plants. Both government and private investors were hesitant to make these necessary investments. The reluctance on the part of private investors was directly related to political uncertainty (guidance). During some periods, large sums were invested to create a market. However, the political commitment to sustain the investments for market formation was often unstable. This led to the earlier described shifts in guidance and market formation. Only in the German case did we observe a very stable institutional setting to allocate the resources needed for market formation.
- Finally, the creation of legitimacy (F7) transpired to be of utmost importance. It is a crucial function that positively helps to align institutions to the need of agents in emerging innovation systems. We observed that the absence of this system function is often an indicator for a poorly functioning innovation system and a weak alignment between institutions and the needs of the emerging innovation system. In most cases the interests of the incumbent innovation system are very well advocated by incumbent lobbying coalitions with enormous lobby power. It proved difficult in most emerging TIS to form advocacy coalitions with enough strength to shape the existing institutional conditions to their needs. We observed that the agents in an emerging innovation system do not easily group together to form a tight network with a clear and strong standpoint. Often, different visions on the best technology and ways to proceed impede the formation of strong coalitions.

Based on the observations above, we conclude that all seven system functions are important variables that influence the realisation of technological innovation systems.

5.2 Are Some Interaction Patterns Generic for Innovation System Dynamics?

Other observations made from the case studies relate to the specific interactions between system functions, key drivers and starting points of the virtuous cycles. For the majority of the virtuous cycles, an important starting point seems to be the urgency of the government to comply with national or international goals on energy or climate change (F4) which triggers research for solutions (F2). In most cases the sequence guidance of the search (F4) – > knowledge development (F2) is observed. Often financial resource mobilisation (F6) is required to make knowledge development possible. This contradicts the linear model where innovation processes are believed to start with either technology push or market demand. Our analysis of innovation system dynamics around sustainable technologies shows that pressure on the incumbent system to look for alternatives and expectations about novel technological trajectories often explain the start of new search processes. These forms of guidance are a much more indirect mode of technology push and market pull than is assumed by the linear model.

Thus most of the sequences start with guidance (F4) and continue with knowledge development (F2), via resource mobilisation (F6). Following this sequence of events, subsequent scenarios all differ from each other, since different agents are involved who act and react in different ways. This shows that the dynamics are complex and that there is not one ideal way to go.

The technology characteristics are another aspect that needs to be considered. A well-functioning, reliable and profitable technology is likely to gather more support and enthusiasm from entrepreneurs, investors and policymakers than a technology that is expensive and unreliable. Thus, positive technological characteristics will result in an easier fulfilment of system functions (e.g. co-firing and combustion). Incumbent actors especially such as energy companies are less reluctant to adopt and lobby for technologies that are similar to their current technologies. In other words, the technological characteristics are very important and influence the fulfilment of the system functions. This also works the other way round, as the system functions influence the technological characteristics (e.g. biomass gasification where no space and time was provided for the technology to develop further and for agents to experiment and gather experience).

In most of the cases an innovation system needs to be constructed from scratch around a new technology. Usually the existing actors, such as energy companies and utilities, resist the change to something new as their business might be endangered, and institutions (tax exemptions, subsidies etc.) are not aligned to the needs of the new technology. In the case of co-firing, the energy companies embrace co-firing as the best solution to comply with the CO_2 reduction targets. The energy companies lobbied for favourable institutional arrangements and implemented biomass co-firing in their coal plants. The contrary occurred for biomass gasification, where the energy companies withdrew all support for gasification projects the moment that the energy market was liberalised, as the technology was unreliable and expensive, which led to the collapse of the biomass gasification innovation system.

Finally, the maturity of the technology affects the functioning of the innovation system. When the technology is still in a nascent stage, system functions like knowledge diffusion and guidance are more important to the functioning of the innovation system than market formation. However, the exact relationship between maturity of the technology and the importance of each of the system functions is still unknown and more research is necessary in this area.

Technology development and establishing the innovation system thus co-evolve in relation to each other. Fulfilling the seven system functions and thereby consolidating the innovation system depend on expectations about the technology itself. Therefore technology development should be successful as to sustain these expectations. At the same time, the system functions are required to stimulate technological development and to raise expectations.

6 Conclusions

6.1 Functions Interact with Each Other

Other than merely testing the system functions we also explored whether system change is related to virtuous and vicious cycles. We compared several case studies of different emerging technologies and observed that indeed the positive interaction between system functions is a very important mechanism for change, i.e. the breakthrough of emerging technologies. Negative interactions between system functions on the other hand hamper the diffusion of the technology and in some cases lead to the collapse of the innovation system. For most case studies we observed that virtuous and vicious cycles alternated, and that a domination of virtuous cycles is the exception.

6.2 Certain Patterns Are Observed (Some Functions Are of Extraordinary Importance)

When the dynamics of virtuous cycles are more specifically observed it becomes clear that a number of system functions play an especially important role. A rise in entrepreneurial activities (F1) is observed when the system functions such as guidance of the search (F4) and/or market formation (F5) are well executed. In several cases the positive guidance (F4) leads to an increase in entrepreneurial activities (F1), but a breakthrough does not occur until a market is formed (F5) that provides entrepreneurs and investors with a long-term, stable perspective. Clear guidance and a well functioning market formation are in turn strongly influenced by the pressure that the entrepreneurs exercise the authorities. A well organised and capable group of entrepreneurs is crucial to build up expectations about the new technology and to successfully influence public policy to adjust the institutional framework conditions so that they are better suited to their needs.

6.3 Limitations

It is important to notice that all cases analysed in this paper deal with sustainable energy technologies. The dynamics of the innovation systems related to these technologies may be quite specific. The energy sector itself is conservative different governments have a very influential role in these trajectories, and innovation processes are strongly influenced by the societal need for clean energy and a reduction of carbon emissions. Further research is required to expand the empirical cases to different sectors and technologies.

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