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Functions of Innovation Systems as a Framework to Understand Sustainable Technological Change: Empirical Evidence for Earlier Claims

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Functions of Innovation Systems as a Framework to Understand Sustainable Technological Change

Empirical Evidence for Earlier Claims

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Abstract

Understanding the emergence of innovation systems is recently put central in research analysing the process of technological change. Especially the key-activities that are important for the build up of an innovation system receive much attention. These are labelled 'functions of innovation systems'. In most cases the authors apply this framework without questioning its validity. This paper builds on five empirical studies, related to renewable energy technologies, to test whether the functions of innovation systems framework is a valid framework to analyse processes of technological change. We test the claim that a specific set of functions is suitable. We also test whether the claim made in previous publications that the interactions between system functions accelerate innovation system emergence and growth is valid. Both claims are confirmed.

Key words: socio-technical change, industrial transformation, technological transition

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1. Introduction

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

In recent literature a structural reorientation of economic activity towards sustainability has been labelled as processes of sustainable socio-technical change, industrial transformation and (socio) technological transitions [1-7]. 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 [5-9].

Due to different disciplinary backgrounds only a limited number of insights from the field of innovation studies are applied to this new and rapid 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 amount of insights in the factors that explain processes of innovation and in the type of policy frameworks that support innovation.

One of the frameworks from innovation studies that has the potential to contribute to understanding sustainable technological change[2] is the innovation system approach. It has become a well-established heuristic framework in the field of innovation studies. It presents insight in the factors that explain processes of innovation [10]. The framework has proven to be successful for policy purposes; it has been adopted as an analytical framework and as guideline for science and innovation policy by numerous public organisations around the world [11-16].

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 [17-29]. More specifically these authors have adopted the technological

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

innovation system (TIS) approach as introduced by [30]. The focus of the TIS approach on the institutions and networks of agents involved in the generation, diffusion, and utilization of a specific technology fits best with their interest in technological change compared to the National Systems of Innovation approach [31, 32] or the sectoral innovation [33] approach that both take a broader perspective.

The central connection between a TIS and socio-technical change is that emerging technologies are developed and applied within the context of a specific TIS. 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 due to specific institutional arrangements that come into place. On the other hand, when a TIS grows the rate of technological progress generally increases which in turn leads to increased success chances of the technology in question. Thus, the maturation of technology and the growth of a TIS is a typical example of co-evolution; they mutually influence each other.

A novel addition by the TIS authors to the earlier innovation system approaches is that these authors have related innovation systems explicitly to general systems theory, as has been used much more in natural sciences, than in social sciences[3]. This has led to a strong focus on innovation system *functioning* since one of the characteristics of a 'system' from a general system perspective is that it has a function, i.e. it is performing or achieving something. This has not been addressed in a systematic manner in the earlier work on innovation systems. Galli and Teubal [22] started some thinking in this direction, which was followed up by Johnson [23], Jacobsson and Johnson [34], Liu and White [25], and Rickne [26]. The primary function of an innovation system is to contribute to the development and diffusion of innovations. Often this is labelled as the goal of the innovation system. The novelty of the work by the authors above is that they reflected on different sub-functions of an innovation system. These authors claim that a number of these sub-functions 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.

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[3] Edquist [34-35] is strongly in favour of making this connection since it might make the innovation system framework more clear and consistent as to serve as a basis for generating hypotheses about specific variables within innovation systems.

However, the system functions approach is not a fully established theoretical framework yet. First of all, different sets of system functions exist in literature [17-21]. This makes it both interesting and challenging to empirically validate which system functions are most relevant to understand technological change and how they interact with each other. The empirical validation of the system functions as proposed in Hekkert et al. [19] is the first goal of this paper. This leads to the following research question: *How suitable is the set of system functions as described in Hekkert et al.* [19] *to describe and analyse the dynamics of innovation systems?*

Second, it has been argued that the interaction between functions may lead to virtuous cycles [17]. It is claimed that these cycles accelerate innovation system growth. Vicious cycles may occur as well slowing down the innovation system growth.. This claim – if validated – has important policy implications. If we are able to comprehend these interaction patterns between functions, we obtain new clues to understand innovation system growth and construct policies to accelerate innovation system growth.

Until now, the analysis method of innovation system dynamics was not suitable to exactly pinpoint the interactions between the system functions. These methods were based on interviewing experts in the innovation system to determine its past and current functioning. Recently a number of case studies have been done that have adopted a different method; the so-called *process method*. This process method is based on the influential Minnesota Innovation Research Programme (MIRP). It is a longitudinal research method that is based on the construction of an event sequence and has proven to be quite powerful in creating insights into the dynamics of innovation [35, 36]. In the studies carried out by Van de Ven and colleagues, a particular innovation project constitutes the level of analysis. In recent studies, the process study approach is adapted and applied to the innovation system level. The second aim of this article is to assess and compare several studies where the innovation system dynamics are analysed by means of the process method. These case studies all focus on emerging sustainable technologies and the innovation system that is analysed is delineated to a technological innovation system.

The question that arises in this context is: *What do interaction patterns of innovation system functions tell us about the dynamics of innovation systems and what sort of interaction patterns can be identified?*

This paper is structured as follows. The theory and concepts used, such as the innovation system and system functions approach will be further described in section 2. A short overview of the process method will be described in section 3. Section 4 will summarise the findings from our earlier case studies on technological innovation system dynamics. For a more thorough description of the case studies, the following references can be consulted [19, 27-29]. In section 5 we present a cross-case analysis by combining the insights from the case studies. Section 6 concludes and discusses the policy implications.

2. Innovation Systems and system functions

There are several definitions of innovation systems mentioned in literature, all having the same scope and derived from one of the first definitions [31]:

> "…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 on a national level, the dynamics are difficult to map, due to 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, qualities of educational systems, university-industry collaborations, and availability of venture capital. Thus, most empirical studies on Innovation Systems do not focus on mapping the emergence of innovation systems and their dynamics [19].

However, in order to understand technological change, one needs insight in how the innovation system around a new technology is build up. Thus insight in the dynamics of the innovation system is necessary. Fortunately, in a technological innovation system (TIS), the number of actors, networks, and relevant institutions are generally much smaller than in a national innovation system; which reduces the complexity. This is especially the case when an emerging TIS is studied. Generally, an emerging innovation system consists of a relative small number of actors 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 [19]. According to Carlsson and Stanckiewicz [30] (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 [24]. A well functioning TIS 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? (Apart from studying the end result: the diffusion of the technology.)

Edquist (2004) 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” [37] (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 [34] 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’[4], i.e. how these functions have been served [34]. 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 [38].

Recently a number of studies have applied the system functions approach, which has led to a number of system functions lists in the literature [17-26]. This paper uses the recently developed list of system functions at Utrecht University [19, 27-29] that will be applied to map the key activities in innovation systems, and to describe and explain the dynamics of a TIS.

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 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)

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" [32]. Therefore, R&D and knowledge

[4] The functional pattern is mapped by studying the dynamics of each function separately as well as the interactions between the functions.

development are prerequisites within the innovation system. This function encompasses ‘learning by searching’ and ‘learning by doing’.

Function 3: Knowledge Diffusion through Networks

According to Carlsson and Stankiewicz [30] the essential function of networks is the exchange of 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 should be affected by changing norms and values. 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’.

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 government goal to aim for a certain percentage of renewable energy in a future year. This event 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.

Function 5: Market Formation

A new technology often has difficulties to compete with embedded technologies. This is especially 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 [39]. 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. This is typically a government’s task.

Function 6: Resource Mobilisation

Resources, both financial and human capital, are necessary as a basic input to all the activities within the Innovation System. And specifically for biomass technologies, the abundant availability of the biomass resource itself is also an underlying factor determining the success or failure of a project.

Function 7: Creation of legitimacy / counteract resistance to change

In order to develop well, a new technology has to become part of an incumbent regime, or has to even overthrow it. Parties with vested interests will often oppose this force of 'creative destruction'. In that case, advocacy coalitions can function as a catalyst 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 of importance. Positive interactions between system functions could lead to a reinforcing dynamics within the TIS, setting off *virtuous cycles* 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: 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 of solutions (F6), which in turn, is likely to lead to Knowledge Development (F2) and increased expectations about technological options (F4). Thus, through interaction the fulfilment of the individual functions is strengthened.

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

3. Methodology

All empirical cases that are compared in this article have 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 [36, 40]. 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.

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, and reports. Lexus Nexus[5] is used as news archive. The archive is complemented with articles from professional journals. The events are stored in a database and classified into event categories. Each event category is allocated to one system function using a classification scheme (see Table 1). During this procedure, the classification scheme was developed in an inductive and iterative fashion. The classification scheme and event categories are verified by another researcher to improve reliability. Any differences in the coding results of the researchers are analysed and resolved.

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

<Insert Table 1 here>

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 for instance an expression of disappointment, or the opposition of an important political group. This is indicated in the allocation scheme by +1 and -1. The balance between positive and negative events yields

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[5] The Lexus Nexus ™ academic news archive contains all articles from a broad selection of newspapers 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 with a keyword search.

specific insights into the slowing down of system growth or into controversies emerging around the analysed technology.

The events are not weighted since the importance of an event is not known beforehand. Only after the construction of the narrative the importance of a specific ‘watershed’ event can be identified.

The counted events could have been analysed statistically using time series analysis methods. However, we have chosen not to apply these methods. The reason for this is that before analysing correlations between different functions over time we first need to obtain qualitative insights in their relations to construct hypothesis. Only then, these hypotheses may be tested using statistical methods.

The final outcome of the process analysis is a narrative (storyline) of how the development of the TIS has changed over time and the role of the different system functions within this development[6]. This narrative is complemented with and illustrated by several pictures in which the events are plotted over time[7]. In the narrative the focus is on extracting interaction patterns between system functions. Based on the content of the events and their chronological order, we are able to deduce the effect of one event onto 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.

Thus, the quantitative exercise is largely intended to strengthen a basically qualitative argument rather than presenting a statistically valid argument by itself.

In this article we use cross case analysis to test whether these patterns are case specific or whether they hold more generally. Insights in these patterns are the first step towards policy recommendations regarding the governance of this set of TIS [19]. In this article we limit ourselves to a very short stylised description of each case where just the main interaction

[6] Due to space limitation no thorough narrative is provided for each case study, since the individual case studies have been published in [27-29; 41] .

[7] The same applies for graphical representation, due to space limitation no graphical representations are provided in this paper but can be found in [27-29; 41].

patterns between system functions are stated. For a more detailed description we refer to the original articles.

4. Results

In this section we provide the empirical material and arguments to answer our research questions. We start with the description of two success cases. Both cases show virtuous cycles. Then we describe two cases where virtuous and vicious cycles alternate. By these cases more insight is provided in the effect of virtuous and vicious cycles. We end with a case where hardly any system functions interact.

4.1 Virtuous cycles building up

We will start with describing the case of biomass digestion in Germany. Biomass digestion is a process to produce a gaseous fuel from organic waste or manure. The main adopters in Germany are farmers that seized the opportunity to convert their excess of manure into renewable energy. The build up of the innovation system starts to take off when the German Government introduces 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 is recognised by entrepreneurs as a key technology to produce renewable energy and they start to create and diffuse knowledge (F2, F3), which leads to the set up of the first digestion plants (F1). The first trials show however that the current legislation is not sufficient to make a good business case for biomass digestion. Lobby activities (F7) by the German Biogas Association try to achieve a change in the institutional conditions. Clearly they are successful when shortly after the German government increases the feed-in rates in 1998 (F4). The level of the feed-in tariffs is such that a first market is formed for biomass digestion (F5), which results in the construction of initially about 200 plants each year (F1), resulting that by the end of 2003 about 1750 plants are standing. However the German Biogas Association and entrepreneurs are not satisfied with the institutional conditions and additional lobby activities (F7) are undertaken to obtain better institutional conditions (F4). These requests quickly find a hearing by politicians, due to the presence of the Green Party in Parliament, and in 2004 higher feed-in tariffs are introduced (F5) that are guaranteed for a period of 20 years; Thereby strongly reducing the uncertainties for entrepreneurs. The feed-in tariffs lead to a market formation, which leads to the final breakthrough of biomass digestion in Germany (F1), i.e. 2700 plants in 2005.

This case shows that the positive interaction between six system functions explains most of the dynamics. The interplay between guidance of 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 in the empirical data. Even though one could say that much knowledge diffusion must have taken place between the farmers (adoptors, entrepreneurs) and the technology suppliers (entrepreneurs), as to improve the technology and achieve such a high diffusion in different regions.

4.2 Virtuous and vicious cycles alternating

The case described above show mainly positive interaction between system functions. This is quite exceptional. In most cases virtuous cycles are alternated by vicious cycles.

In the second case clear virtuous and vicious cycles are observed. This is the case of biomass co-firing. This implies adding biomass as a feedstock to existing coal fired power plants. This add-on technology is quite simple compared to other sustainable energy technologies. Moreover, there is no need to build up a complete innovation system from scratch. In this innovation system the actors, power plants and infrastructures are already in place, being part of the incumbent system. Nonetheless, the dynamics and sequence of events are interesting. The sequence of events starts with guidance of the government, stimulating the energy companies to reduce CO_2 emissions (F4). The energy companies comply by publishing an ‘Environmental Action Plan’. This changes the direction of search towards alternatives for coal as feedstock. Co-firing is quickly recognised as a very promising option (F2). The government supports the ambitions of the energy companies to replace a certain percentage of coal with biomass, by the provision of resources (F6) and the formation of a market (F5) (the power producers received a subsidy for each kWh produced with biomass). This leads to the quick introduction of co-firing (F1). However, around 2000 a vicious cycle starts. Unclear and contradictory regulations regarding biomass co-firing (-F4) temporarily delay the entrepreneurial activities (-F1). The vicious cycle is broken by lobby activities by the energy companies (F7). This leads 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 forms an additional market for biomass co-firing by negotiating another voluntary agreement with the coal sector to reduce CO_2 emissions. (F5). This is the final trigger to implement co-firing in all coal-fired power plants (F1).

The third case also shows alternating virtuous and vicious cycles, but now the vicious cycle dominate. This is the case of biomass gasification. This is a very high-tech conversion method to convert biomass very efficiently into electricity. The biomass gasification innovation system starts by the recognition of the potential of this technology by a small group of energy specialists. Positive experiences in Finland (F3) guide these Dutch energy specialists to focus on this novel technology (F4). The time is ripe for this technology due to a waste surplus problem and the climate change issue on the political agenda (F4). Several desktop and feasibility studies on biomass gasification provide very positive results (F2). Due to these positive results and great enthusiasm of the energy experts, the expectations (F4) of the entrepreneurs and government are boosted to high levels in a short time span. As a natural consequence subsidies are provided for research (F6) and research programmes are set up (F2). The high enthusiasm and high-strung expectations lead to the set up of two biomass gasification projects (F1). The above shows a strong virtuous cycle during the period 1990 – 1998, where positive expectations (F4) strongly influences positive system dynamics.

However, the virtuous cycle is terminated at once due to one key event: the liberalisation of the energy market. This change of the institutional setting leads to the situation where energy companies compete for customers. In addition they also start to compete in terms of energy prices, which lead to unproven, risky projects being the first to be terminated. A vicious cycle starts to take place. The lack of support by energy companies (-F4) results in less knowledge creation (-F2), less investments (-F6), less resources (-F6) and above all negative expectations (-F4). These negative events reinforce each other and result that no more activities are carried out anymore, so that the system collapses within a couple of years. Since then biomass gasification is still not diffused on large-scale.

The fourth case deals with the development of biofuels in the Netherlands based on [28]. In this storyline biofuels are biomass based liquid fuels for automotive purposes that may serve as a substitute for diesel. It is important to make a distinction between first and second-generation biofuels. First generation biofuels are based on rapeseed oil. The production process does not require advanced or complex technology. For second-generation biofuels woody material (lignocelluloses) is used as feedstock. Highly complex chemical process technology is needed to transform woody material into diesel substitutes. The build up of the innovation system around biofuels in the Netherlands is strongly influences by discussions on which of these technologies should be pursued. The developments start with experiments (F1) around first generation biofuels in 1990. Policy programs by the European Union and similar activities in Germany provide guidance for starting these initiatives (F4). Lobby practices (F7) for tax exemptions are successful for different projects and small niche markets are created by these tax exemptions (F5). Different scientific report provide negative guidance (-F4) by stating that first generation biofuels are not a sound technological trajectory to pursue in the Netherlands due to too little environmental benefits and high costs. The government is in doubt what to do with these developments and do not provide clear guidance towards this technology (-F4). This leads to the situation that for individual projects is it sometimes possible to get a tax exemption but that no general tax exemption is put into practice. No real motor is visible in this period.

In 1998 the government initiates a technology development program for the development of new fuels. Quickly after the start of the program, a choice is made to focus specifically on second-generation technology and not on first generation technology. The technology program sets in motion the interaction between many system functions. Resources are provided (F6) to stimulate the formation of networks (F3) and to support assessment research (F2). This in turn leads to different projects (F1) .The projects are successful (F4), particularly with respect to solving important technical bottlenecks (F2). The programme serves as a catalyst that bundles and guides R&D-projects that have, till then, been going on in relative isolation (F3, F4). As a consequence multiple entrepreneurs (F1) start new biofuels projects during this episode, even outside the program. A clear knowledge – entrepreneur motor starts to develop in this period.

The final outcome of the program should be the construction of an demonstration plant for second generation biofuels. The government was willing to co-invest. However, it turned out that the parties were not willing to take the economic risks associated with the construction of such a plant (-F1). The lack of a promising market (-F5) proved to be the primary reason.

The analysis shows that a lack of vision and guidance (-F4) led to poor market formation activities for the first generation biofuels (-F5) and thereby the Dutch government not only slowed down the progress for first generation technology but unintentionally also for second generation technology. The earlier observed motor comes to an end.

Things change in 2003 as the EU issues the Biofuels Directive [41]. This exogenous factor has drastic consequences. In contrast to the Dutch government, the EU is largely oriented towards 1G biofuels. With the new task of translating the EU directive to national policy, the national government reorients its policy. From 2003 on, the technology program is given a new priority task (F4): the development of a generic market for biofuels. The 1G technologies are now increasingly perceived as bridges towards 2G fuels implementation [41]. This changes the entrepreneurial climate and many regional entrepreneurs execute plans for the construction of small factories (F1). The projects are supported by a large number of actors; amongst them are farmers, farmers' associations and local government authorities (F3). Many of them are made shareholders (F6). Also, biofuels are promoted to potential users (F4). For these projects to financially work out, tax exemptions are requested (F7), and issued on project basis (F5). By 2005, the first (1G) bio-diesel plant is built. This successful outcome (F4) triggers a pattern of cumulative causation that can coined as a market-motor and from 2002 on, numerous projects (F1) start all over the country, especially in rural areas.

Thus the developments around biofuels in the Netherlands can be characterized by the fact that after a period of low interaction between system functions, periods of virtuous cycles are alternated by periods of vicious cycles.

To summarise, the case studies described above show that the interactions between system functions lead to the (temporal) build up 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. Contrary to the success of this technology in Germany, the Dutch case is a complete failure. 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 period of the emergence of the biomass digestion innovation system (1974-1987) only the system functions knowledge development (F2) and entrepreneurial activities (F1) occur as several pilot plants are set up as solution to the manure surplus problem (F4). However, no other system functions are triggered. In the following years, negative guidance against biomass digestion (-F4), as the manure surplus is not solved, hinders any market formation (-F5) and investments (-F6). Surprisingly very little lobby activities occur (-F7). The biomass digestion entrepreneurs seem very weakly organised. Only in 1989 a cautious built-up of system functions occurs when guidance (F4), due to a waste surplus, where biomass digestion seems to be an potential solution, stimulates the knowledge creation and diffusion (F2 and F3) of biomass digestion, resulting in the set up of several plants (F1), seven plants in 1992. However system functions, such as market formation (-F5) and resource mobilisation (-F6) remain unfulfilled. Also lobby activities are scarce to improve institutional conditions for digestion. One of the institutional barriers for manure digestion is that it is not allowed to add other biomass feedstock to the digester. This is called co-digestion. If this would be allowed the biogas output of a digester is greatly increased and thereby also the profitability of the plant.

In 1995 the positive guidance turns into negative guidance (-F4), as biomass digestion is not seen as a renewable energy technology. Where the German entrepreneurs were able to show the German government that digestion is a well functioning renewable energy technology that deserves support, the Dutch digestion sector did not manage. No additional resources are therefore made available (-F6), forcing several plants to shut down (-F1). In 2003, the Dutch government aims to increase the share of green electricity (F4) and introduces a feed-in tariff system (F5). Due to this change in institutional conditions, actors of the biomass digestion sector see an opportunity to profit from this market formation (F5) and this time start a successful lobby to allow co-digestion and to put biomass digestion as a renewable energy technology on the political agenda (F7). Finally, between 2004 and 2006 an increase of biomass digestion plants occurs (F1).

To summarise, between 1974 and 2003 no continuous built up of system functions occurs. Some system functions are fulfilled but they do not interact with each other as to reinforce each other and trigger other system functions. This provides a scattered functional pattern that leads to an innovation system that is muddling through, resulting in a very low diffusion rate of the technology in question. However, it still provides a seeding ground for virtuous cycles in a much later stage when the institutional conditions have changed.

5. A cross-case analysis

5.1 Are all functions relevant?

Now that we know that processes of virtuous and vicious cycles actually occur it becomes possible to test whether all seven functions are relevant as key factors that drive innovation system growth. We apply two different methods to answer this research question. First, based on the different event databases it is possible to count how many events are allocated to each system function and to calculate the share of each system function per case study and in total in percentages (see Table 2). Second we argue based on the earlier described cases what the relative importance is of the different system functions.

To start with the first method, we observe that all seven system functions used in the empirical analyses can be related to actual events that took place. This is an important observation since the absence of one or more system functions in the event databases might mean that these system functions are not relevant for understanding the build up of innovation systems. We also observe a difference in the amount of events allocated to each system function. This does not mean that the system functions with the highest percentage (most events) are the most important ones. To some system functions many events may be allocated where the total influence may be lower than a small number of events for other system functions. Thus, since the importance of an event can only be known retrospectively, it is better not to weigh the events at all.

Thus, Table 2 creates first evidence that all seven system functions matter, but not with respect to the importance of each system function.

<Insert Table 2 here>

In order to understand which system functions are more important than others, it is necessary to apply the second method, which is based on the narratives that describe the dynamics of the individual TIS; it should become clear which system function turns out to be a strong driver for system change and which system functions impede system growth.

- Entrepreneurial activities proved to be a prime indicator whether an innovation system progresses or not. First, we observed that it is a very good indicator for technology diffusion. In most cases technology diffusion developed in line with entrepreneurial action. Second, entrepreneurial activities proved to be central function that connects other system functions and thereby adds to the occurrence virtuous cycles. We often observed knowledge creation being followed by entrepreneurial activities and in turn entrepreneurial activities triggered many other system functions.
- Knowledge development (F2) also proved important in all cases. This is not surprising since we studied complex technologies in 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 entrepreneurial activities. 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 that they encounter are solved by additional R&D efforts. An important finding is that knowledge development needs to be defined much broader than knowledge about 'how a new technology functions or performs'. Very often important processes of knowledge development are related to creating insights in 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 those novel technologies are 'new combinations' of already existing technologies, either transferred from another sector (digestion technology was already used in the 70s for wastewater treatment) or used with a different feedstock (biomass gasification could benefit from experience with coal gasification).
- The role of knowledge diffusion proved to be more difficult to map directly. We have been able to measure the 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 relations that are not reported in literature. So, many of the knowledge exchange processes do not become visible using this method. By means of interviews actors in the innovation system, much more insight can be provided into the fulfilment of this function. Thus, the quantitative method is not optimal 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 proved to be an important system function. It stood at the base of many developments and led 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 due to other factors like problematic technological performance and availability of capital.
- Market formation proved to be in most cases the final trigger that leads to innovation system growth. Very often it is one of the last functions to be addressed, after which the build-up of the system really accelerates. For example, we observed that the success of biomass combustion in the Netherlands is directly related to the fulfilment of 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 turned out to be relevant in each case study. In most cases it was not difficult to persuade the government to allocate resources for knowledge development. Through these capital injections many knowledge development projects were started. It proved much more difficult to mobilise resources to build and

construct plants. Both government and private investors were hesitant to provide these necessary investments. The reluctance by private investors was directly related to political uncertainty (guidance). During some periods huge amounts of resources were invested to create a market. However, the political will 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 we observed a very stable institutional setting to allocate the needed resources for market formation.

- Finally, the creation of legitimacy proved to be of utmost importance. It is a crucial function that positively helps to align institutions to the need of actors 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 poor alignment between institutions and the needs of the emerging innovation system. In most cases the interests of the incumbent innovation system are very well put to the front by incumbent advocacy coalitions with enormous lobby power. It proved difficult in most emerging TIS to form advocacy coalitions with enough strength to align the existing institutional conditions to their needs. We observed that the actors in an emerging innovation system do not easily pack together to form a tight network with a clear and strong standpoint. Often, different visions on the most ideal technology and ways to proceed impede strong coalition formation.

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

5.2 Are some interaction patterns generic for innovation system dynamics?

Other observations that are made across 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 of the cases the sequence guidance (F4) -> knowledge development (F2) is observed. Often financial resource mobilisation (F6) takes place 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 way of technology push and market pull then that the linear model assumes.

Thus most of the sequences start with guidance (F4) and continue with knowledge development (F2) via resource mobilisation (F6); however the following sequences all differ from each other. There are not more than two identical sequences, since different actors are involved, which act and react in different ways. This shows that the dynamics are complex and that there is not one ideal way of how it can go.

However, some functions proved to be key drivers that influence system change. A rise in entrepreneurial activities is observed when the system functions such as guidance of the search (F4) and/or market formation (F5) are well fulfilled. In several cases the positive guidance (F4) is responsible for 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 put on the authorities. A well organised set of entrepreneurs, that is capable of building up expectations about the new technology and is successful in influencing the government to adjust the institutional conditions in such a way that they are better aligned with their needs, is crucial.

Yet, another aspect that needs to be considered, are the technology characteristics. A well functioning, reliable and profitable technology is likely to gather more support and enthusiasm by entrepreneurs, investors and policy makers than a technology that is expensive and unreliable. Thus, positive technological characteristics will result that system functions are more easily fulfilled (i.e. cogeneration, co-firing and combustion were little technical problems occurred). In other words, the technological characteristics are very important and influence the fulfilment of the system functions. However this is true the other way round as well, as the system functions influence the technological characteristics (i.e. biomass gasification where no space and time was provided for the technology to further develop and for actors to experiment with it and build up experience). Finally, the maturity of the technology has effects on the functioning of the innovation system. When the technology is still in a very emerging stage, system functions like knowledge diffusion and guidance are more important to the functioning of the innovation system than market formation. However, the exact relation between the maturity of technology and the importance of each of the system functions is still unknown and more research is necessary in this area.

Thus technology development and innovation system build-up co-evolve. The fulfilment of the seven system functions and thereby the build-up of the innovation system depend on expectations about the technology itself. Therefore technology development should be rather successful as to maintain these expectations. At the same time, the system functions are required to stimulate technological development and to raise expectations.

6 Conclusions and strategy recommendations

In the section below we will provide answers to the research questions posed at the beginning of the paper - testing the suitability of the system functions selected and the functional pattern identified.

All functions are relevant

Our analyses showed that the system functions that were proposed in Hekkert et al. [19] all matter. By allocating the events to each system function we could determine whether one of the system functions is superfluous. It turned out that this is not the case. We recognised that for system function 3: knowledge development, the method of archive research was not as suitable as for other system functions, as not many specific events for knowledge diffusion could be identified.

Not all events found in literature could be allocated to one of the system functions. One other category that would comprise the unallocated events is ‘external factors’. This covers events like oil crises, Chernobyl, power shortages in California, and international climate change agreements. These events have been included in the narrative but not conceptualised in a formal way. Thus, the approach focuses in its conceptualisation of technological change much more strongly on activities endogenous to the innovation system than exogenous factors.

It is of course possible to come up with a different set of functions using the same empirical material. Our analysis started by retrieving many events from literature, categorising those in a limited set of event categories and finally allocating these event categories to the seven functions. Each event category is specific to one function. However, another group of researchers with different backgrounds might highlight different processes and come to a different categorisation of events and thereby to a different set of functions. The basic difference between these lists of functions would be that some functions are divided into more specific functions while others are presented in a more aggregated form. We have not done the exercise to show that our set of events and event categories could or could not be allocated to the other lists of functions presented in literature.

Furthermore, we observed that more events could be allocated to some system functions than to others, but that the quantity does not mean that the system function with more events is more important than a system function with fewer events. In fact we deduce that for some system functions, such as market formation, the impact of the event is higher than for events allocated to knowledge development, and that there are less of such high impact events. Finally, we restrain from weighing events as the importance of each event can only be known from hindsight and would therefore bias the storyline.

Functions interact with each other

Besides testing the system functions we also want to know whether system change is related to virtuous and vicious cycles. We compared several case studies of different emerging technologies with each other 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 instead hamper the diffusion of the technology and in some cases provoke the collapse of the innovation system. For most case studies we observed that virtuous and vicious cycles altered, and that there are only exceptions where only virtuous cycles dominate.

Certain patterns are observed (some functions are of extraordinary importance)

Looking more specifically at the dynamics of virtuous cycles, 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 fulfilled. In several cases the positive guidance (F4) is responsible for 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 put on the authorities. A well organised set of entrepreneurs is crucial, that is capable of building up expectations about the new technology and is successful in influencing the government to adjust the institutional conditions in such a way that they are better aligned with their needs.

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 might 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 therefore necessary to expand the empirical cases to different sectors and technologies.

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Appendix

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, R&D projects, patents	+1
Function 3: Knowledge Diffusion	Conferences, workshops, platforms	+1
Function 4: Guidance of the Search	*Positive* expectations of renewable energies; *Positive* regulations by government on renewable energies	+1
	Negative expectations of renewable energies; *Negative* regulations by government on renewable energies	-1
Function 5: Market Formation	Feed-in rates, environmental standards, green labels	+1
	Expressed lack of feed-in rates, lack of environmental standards, lack of green labels	-1
Function 6: Resource Mobilisation	Subsidies, Investments	+1
	Expressed lack of subsidies, investments	-1
Function 7: Advocacy Coalition	Lobby by actors to improve technical, institutional and financial conditions for particular technology	+1
	Expressed lack of lobby by actors; Lobby for other technology that competes with particular technology; Resistance to change by neighbours (NIMBY attitude)	-1

Table 2 – Overview of the share of system function per case study in percentages

System functions	Biomass Digestion NL	Biomass Digestion D	Biomass Gasification	Biomass Combustion	Biofuels	Total % per SF
Function 1: Entrepreneurial Activities	12	21	21	11	9	**13**
Function 2: Knowledge Development	22	8	22	17	30	**21**
Function 3: Knowledge Diffusion	14	4	11	5	4	**12**
Function 4: Guidance of the Search	27	25	34	37	40	**27**
Function 5: Market Formation	5	21	1	5	1	**9**
Function 6: Resource Mobilisation	6	9	8	13	5	**5**
Function 7: Advocacy Coalition	14	13	3	13	11	**13**