Dynamics of Technological Innovation Systems: Empirical Evidence for Functional Patterns

Simona O. Negro Marko P. Hekkert
Utrecht University, Copernicus Institute for Sustainable Development and Innovation, Department of Innovation Studies, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands
(E-mail: s.negro@geo.uu.nl, m.hekkert@geo.uu.nl)

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’. This paper builds on seven 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 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

1 Introduction

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

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

One of the characteristics of a ‘system’ is that it has a function, i.e. it is performing or achieving something. However, this has not been addressed in a systematic manner in the earlier work on innovation systems. Galli and Teubal (1997) started some thinking in this direction, which was followed up by Johnson (1998), Jacobsson and Johnson (2000), Liu and White (2001), and Rickne (2001). These authors claim that a number of system functions are considered to be important for an innovation system to develop and, thereby, to increase the success chances of the emerging technology.

However, the system functions approach is not a fully established theoretical framework yet. First of all, different sets of system functions exist in literature (Edquist and Johnson 1997; Bergek 2002; Carlsson and Jacobsson 2004; Jacobsson and Bergek 2004; Hekkert, Suurs et al. 2007). 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. (2007) 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. (2007) to describe and analyse the dynamics of the TIS?*

Second, several authors claim that the interaction between functions may lead to virtuous cycles, also cumulative causation (Jacobsson and Bergek 2004). It is claimed that these mechanisms of cumulative causation accelerate innovation system growth. On the other hand, also vicious cycles may occur. In this case negative feedbacks between system functions slow down or even stop system growth. This claim is very exciting. If we are able to comprehend these cumulative causation mechanisms, we have the key to understand innovation system growth and thereby the key to accelerate innovation processes.

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 (Van de Ven 1990; Van de Ven, Polley et al. 1999). In the studies carried out by Van de Ven and colleagues, the level of analysis lies on a particular innovation project. In the recent empirical case 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 is analysed by means of the process method.

The question that arises in this context is: *What do functional patterns tell us about the dynamics of Technological Innovation Systems and what sort of functional 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 present the most important findings that result from combining the insights from several studies on innovation system dynamics. For a more thorough description of the case studies, the following references can be consulted (Hekkert, Harmsen et al. 2007; Negro 2007; Negro, Hekkert et al. 2007; Suurs and Hekkert 2007; Negro, Suurs et al. 2008).

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 (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 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 dynamics (Hekkert, Suurs et al. 2007).

However, in order to understand technological change, one needs insight into the dynamics of the innovation systems. In a 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, the TIS might be a good system delineation to study dynamics and to come to a better understanding of what really takes place within innovation systems (Hekkert, Suurs et al. 2007). According to Carlsson and Stanckiewicz (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 well functioning TIS is a requirement for the technology in question to be developed and widely diffused. In fact, large-scale diffusion cannot take place without a well functioning TIS. But what is it that determines whether or not a TIS functions well and how do we find out? (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" (Edquist 2004a) (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'

95, i.e. how these functions have been served (Johnson and Jacobsson 2000). The system functions are related to the character of, and the interaction between, the components of an innovation system, i.e. actors (e.g. firms and other organisations), networks, and institutions, either specific to one TIS or 'shared' between a number of different systems (Edquist 2001).

---

95 The functional pattern is mapped by studying the dynamics of each function separately as well as the inter-dependencies between the functions.

Recently a number of studies have applied the system functions approach, which has led to a number of system functions lists in the literature. This creates unanimity about which system functions are relevant. This paper uses the recently developed list of system functions at Utrecht University (Hekkert, Suurs et al. 2007) to map the key activities in innovation systems, and to describe and explain shifts in Technological Innovation Systems[96].

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)

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

Function 3: Knowledge Diffusion through Networks

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

Function 4: Guidance of the Search

The activities within the Innovation System that can positively affect the visibility and clarity of specific wants among technology users fall under System Function: Guidance of the Search. 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, therefore it is important to create protected spaces for new technologies. One possibility is the formation of temporary niche markets for specific applications of the technology (Schot, Hoogma et al. 1994). Another possibility is to create a temporary competitive advantage by favourable tax regimes or minimal consumption quotas.

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: Advocacy Coalitions (Creation of legitimacy / counteract resistance of 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; they put a new technology on the agenda (F3), lobby for resources (F6), favourable tax regimes (F5) and by doing so create legitimacy for a new ‘technological trajectory’ (Sabatier 1988; Sabatier and Jenkinssmith 1988; Sabatier 1998). If successful, advocacy coalitions grow in size and influence and may become powerful enough to brisk up the spirit of creative destruction

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 (see Figure 1, representing possible virtuous cycles).

---

[96] This list of system functions has been, to a large extent, developed in agreement with colleagues from Chalmers University (Sweden) to be applied to empirical work both in the Utrecht and the Chalmers group.

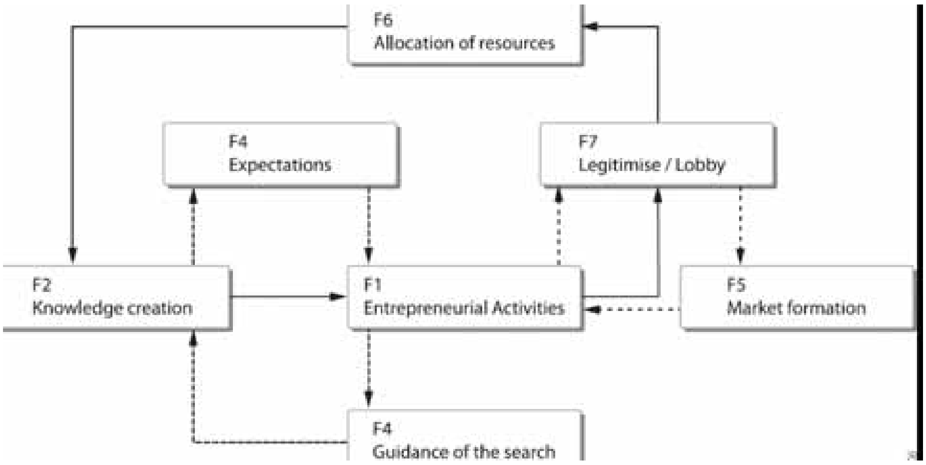

Figure 1 Overview of Possible Einforcing Cycles within an IS

On the basis of empirical data, the interactions between the functions can be assessed, whether a positive or a negative cycle takes place. Since we have defined seven system functions, many possible interactions are possible. However, the number of starting points is likely to be much smaller. We expect to observe certain interaction patterns more often than others. 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 Function 4: Guidance of the Search. In this case, societal problems are identified and government goals are set to limit environmental damage. These goals legitimise the mobilisation of resources to finance R&D projects in search of solutions (F6), which in turn, is likely to lead to Knowledge Development (F2) and increased expectations about technological options (F4). Another virtuous cycle that we expect to occur regularly starts with entrepreneurs lobbying for better economic conditions to make further technology development possible (Function 7). They may either lobby for more resources to perform R&D, leading to higher expectations, or they may lobby for market formation, since very often a level playing field is not present. If this lobby leads to the formation of markets (F5), an entrepreneurial activities boost is expected (F1), leading to more knowledge formation (F2), more experimentation (F1), increased lobbying (F7) for even better conditions, and high expectations guiding further research (F4). Many other combinations are possible; the causality is bound to be very complex, for example when different system functions enhance each other.

Vicious cycles are also possible, where a negative function fulfilment leads to reduced activities related to other system functions, thereby slowing down or even stopping the progress. For example, if the expectations of a technology are high (F4) but the practical results are disappointing, a collective disillusionment in the technology (-F7) may rise, causing no more projects to be set up (-F1). This may reduce the amount of activities for knowledge development (F2) and availability of resources (-F6). Another possible vicious cycle is the lack of consistent government guidance (-F4), resulting in the absence of a market (-F5), so that no prospect is provided for entrepreneurs to set up projects (-F1). This may, subsequently, lead to less support and lobbying (-F7) for better institutional conditions (-F4) and so forth, until the system eventually collapses.

3 Methodology

The method we use to map functional patterns is inspired by the ‘Historical Event Analysis’ as used by Van de Ven and colleagues (Van de Ven, Polley et al. 1999; Poole, van de Ven et al. 2000). Stemming from organisational theory, the usual focus is on the firm and firm networks; in our case, the analysis is applied to a technological system level.

Basically, our 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[97] 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

---

[97] The Lexus Nexus TM academic news archive contains all articles that have been published from 1990 onwards. It is quite a homogeneous source that allows for quantification of the data retrieved. Relevant articles can be found with a keyword search.

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.

Table 1 Operationalisation of System Functions

System Functions	Event category	Sign/Value
Function 1: Entrepreneurial Activities	Project started Contractors provide turn-key technology	+1
	Project stopped Lack of contractors	-1
Function 2: Knowledge Development	Desktop-, assessment-, feasibility studies, reports	+1
Function 3: Knowledge Diffusion	Conferences	+1
Function 4: Guidance 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

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

Thus, the final outcome of the process analysis is a narrative (storyline) of how the development of the Technological Innovation System has changed over time and the role of the different system functions within this development[98]. This narrative is completed with and illustrated by several pictures in which the events are plotted over time[99]. In the narrative the focus is on extracting patterns like the cycles represented in Figure 1.

The construction of the cycles is based on empirical data and not on statistical data. 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 functional patterns.

Cross case analysis can then be used 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 Technological Innovation Systems (Hekkert, Suurs et al. 2007).

---

[98] Due to space limitation no thorough narrative is provided for each case study, since the individual case studies have been published in (Hekkert, Harmsen et al. 2007; Negro 2007; Negro, Hekkert et al. 2007; Suurs and Hekkert 2007; Negro, Suurs et al. 2008)

[99] The same applies for graphical representation, due to space limitation no graphical representations are provided in this paper but can be found in (Hekkert, Harmsen et al. 2007; Negro 2007; Negro, Hekkert et al. 2007; Suurs and Hekkert 2007; Negro, Suurs et al. 2008)

4 Results

In this section we provide the empirical material and arguments to answer our research questions. We are both interested in the question whether all seven system functions as proposed in Hekkert et al. (2007) are relevant and whether processes of virtuous and vicious cycles actually can be reconstructed based on detailed empirical analyses.

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 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.

The case of cogeneration in The Netherlands shows different dynamics, but also in this case, virtuous cycles are observed. Cogeneration is a very efficient energy conversion technology where the excess heat that normally is lost during the production of electricity is used for heating purposes. Thereby the overall efficiency of primary energy conversion into useful energy is greatly improved. The dynamics of the cogeneration innovation system is a very complex story and spans a long time period (1980 – 2005). A thorough description of the case can be found in (Hekkert, Harmsen et al. 2007). In this paper a simplification of the complex dynamics are provided.

For a long time industrial cogeneration existed in a niche market (F5) where knowledge and resources were available (F2, F6). Then the Dutch government recognises the potential of cogeneration and undertakes several actions during many years to stimulate the diffusion of cogeneration. The government increases the legitimacy of cogeneration (F7) by installing a commission to study the barriers for cogeneration diffusion. They take the recommendations of the committee seriously and start to work on function 6: resource mobilisation. Capital becomes available for industry to invest in cogeneration, which leads to some projects (F1) and a significant amount of knowledge development (F2). It is not so much fundamental knowledge development as creating insight in the potential of cogeneration in different sectors and companies. These insights lead to more projects (F1). Experiences are well shared between cogeneration users (F3) and a first lobby takes place urging the Dutch government to make the investments in cogeneration more interesting by increasing the market price of electricity produced by means of cogeneration. These lobby activities are successful and new laws come into practice. This immediately leads to more projects (F1). The real explosion in cogeneration activities occurs when the legitimacy for cogeneration increases enormously due to the increasing importance of

CO_2 emissions on the political agenda (Kyoto protocol) (F7). This results in voluntary agreements between the Dutch industry and government to reduce carbon emissions by 20%. This creates a very large market for cogeneration (F5). The Dutch industry has to reduce emissions and cogeneration is available as a well functioning technology that could fulfil the industry obligations for a large part. The last steep increase in diffusion is supported by investment subsidies (F6) and a cogeneration broker that becomes a pivot in knowledge diffusion (F3).

Thus also this case shows the important interaction between most system functions. The final trigger is the system function market formation.

4.2 Virtuous and Vicious Cycles Alternating

The two cases 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 third 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 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 CO2 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 such 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 fourth 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. Even though the technology originates from the Second World War period, it can be regarded as a radical innovation compared to current ways of converting biomass into useful energy. 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 leads to that unproven and risky projects are 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 fifth case deals with the development of biofuels in the Netherlands (Suurs and Hekkert 2007). 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 influenced by discussions about which of these technologies should be pursued.

The developments start with experiments (F1) around first generation biofuels in 1990. Policy programmes 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 reports 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. Government is in doubt what to do with these developments and does 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.

In 1998 the government initiates a technology development programme for the development of new fuels. Quickly after the start of the programme, a choice is made to focus specifically on second-generation technology and not on first generation technology. The technology programme 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 programme. The final outcome of the programme should be the construction of a demonstration plant for second generation biofuels. The government agrees to co-invest. However, it turns out that the parties are not willing to take the economic risks associated with the construction of such a plant (-F1), primarily due to the lack of a promising market (-F5).

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 interactions between the system functions come to an end.

Things change in 2003 as the EU issues the Biofuels Directive (Suurs and Hekkert 2007). This exogenous factor has drastic consequences. In contrast to the Dutch government, the EU is largely oriented towards first generation biofuels. With the new task of translating the EU directive to national policy, the national government reorients its policy. From 2003 on, the technology programme is given a new priority task (F4): the development of a generic market for biofuels. The first generation technologies are now increasingly perceived as bridges towards the implementation of second generation fuels (Suurs and Hekkert 2007). 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 agents; 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 be financially attractive, tax exemptions are requested (F7), and issued on project basis (F5). By 2005, the first (first generation) bio-diesel plant is built. This successful outcome (F4) triggers a pattern of cumulative causation that can be coined as a market-driven cycle 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 characterised by the notion that after a period of low interactions between the system functions, periods of virtuous cycles are alternated by periods of vicious cycles and vice versa.

The sixth case is about solar photovoltaic energy (PV). PV is the direct conversion of light into electricity, i.e. electric potential and a current. There is a wide range of solar cell material and approaches that have been developed and applied or are still being developed.

The first solar cell was invented in the 50's but it took another 40 years before PV would play a role in the Netherlands. In the 90's the Dutch government made an important contribution by introducing several financial stimulations (F6), which resulted in research and projects (F2). Due to positive results expectations increased about PV to contribute to a sustainable energy supply in the Netherlands, so that at the end of the nineties PV was seen as the most promising option of renewable energy technologies (F4). This resulted in a continuous increase of installed PV systems, where a peak of 19.6 MW installed was reached in 2003 (F1). However, the costs had not decreased and the efficiency had not increased in the meantime, which led to a lot of criticism and discussions whether it was useful to continue to support PV (-F7). An evaluation of the financial support showed that PV was heavily subsidized in comparison to other renewable energy options. This resulted that a lot of financial support and tax exemptions were abolished (-F6) shortly after, resulting in a collapse of the PV market in the Netherlands (-F5) (the yearly installed capacity from 2004 to 2007 dropped from 3.6 MW, to 1.7 MW, to 0.3 MW to 1.5 MW respectively). After 2003 PV did not play a role anymore in the Netherlands, as there was no market anymore (-F5). As a consequence the Dutch PV sector focussed their activities on export. This again resulted that there was less demand for PV (-F5) and that less financial (-F6) and political support (-F4) was provided. The absence of an effective support scheme was lacking towards the first half of the twenty-first century, which in turn resulted in the drop of the Dutch market to almost zero in 2006 (-F5). The producers focussed on the export market and most of the investors were discouraged by the unreliable policies of the Dutch government (-F4).

This case shows that a build-up of several System Functions was occurring until the turn of the century, such as guidance of the search (F4) triggering knowledge creation (F2), entrepreneurial activities (F1), resource mobilisation (F6), and market formation (F5) to occur. However, in the beginning of the twenty first century, a change in institutional conditions (i.e. lack of financial and political support) triggers a vicious cycle, where negative guidance against PV (-F4) hinders any market formation (-F5), investments (-F6) or lobbies to occur (-F7) and finally the discontinuation of entrepreneurial activities (-F1). These negative events reinforce each other and result that less activities are carried out. The amount of projects considerably decreased as well as the installed capacity of PV per year. Ever since then, PV has failed to diffuse 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) build up or deconstruction of emerging innovation systems.. 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 Limited Interaction between System Functions

To illustrate these types of dynamics 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 a potential solution, stimulates the knowledge creation and diffusion (F2 and F3) of biomass digestion, resulting in the set up of several plants (F1), i.e. 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 easily collapses when some system functions are negatively fulfilled.

5 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. The explanation for this is the following. The databases are constructed in such a way that the events are not weighed. 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. Why not weigh the events as a solution to this problem? Then one would need to know beforehand how important each event is. Since this is an impossible task, as the importance of an event can only be known retrospectively, it is better not to weigh the events at all.

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

Table 2 Overview of the Share of System Function Per case Study in Percentages[100]

System Functions	Biomass Digestion NL	Biomass Digestion D	Biomass Gasification	Biomass Combustion	Biofuels	PV	Total % per SF
Function 1: Entrepreneurial Activities	12	21	21	11	9	20	**13**
Function 2: Knowledge Development	22	8	22	17	30	8	**21**
Function 3: Knowledge Diffusion	14	4	11	5	4	28	**12**
Function 4: Guidance of the Search	27	25	34	37	40	4	**27**
Function 5: Market Formation	5	21	1	5	1	24	**9**
Function 6: Resource Mobilisation	6	9	8	13	5	3	**5**
Function 7: Advocacy Coalition	14	13	3	13	11	13	**13**

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 Technological Innovation Systems; it should become clear which system function turns out to be a strong driver for system change and which system functions impede system growth.

To start with system function 1: *entrepreneurial activities*, proved to be a crucial prime indicator, whether an innovation system progresses or not. In the case of biomass digestion in Germany a great increase of plants constructed could be observed after alternation in the institutional conditions and by

---

[100] Due to slight differences in execution of the case studies, the database for co-generation was not accessible.

2005 about 3000 plants were constructed producing 800 MW. In comparison to the Dutch biomass digestion case where every other year a plant was constructed and shut down, no continuous diffusion of the technology is observed and by 2005 only a handful of plants are still standing.

Knowledge development (F2) also proved important in all cases. Very often knowledge development preceded entrepreneurial activities or co-evolved with entrepreneurial activities. An important finding in this respect 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 (coal gasification was used in the second world war as no petrol was available).

The role of *knowledge diffusion (F3)* proved to be more difficult to map directly. However, we did observe many interactions between actors, resulting in a different course of action. Implicitly we may assume that knowledge diffusion and even learning has taken place. In the case of biomass digestion in Germany, one could say that much knowledge diffusion must have taken place between the farmers (adopters, entrepreneurs) and the technology suppliers (entrepreneurs), as to improve the technology and achieve such a high diffusion in different regions.

Guidance of the search (F4) proved to be a very determinant system function. It stood at the base of many developments and led to several courses of action, either positive or negative. In the case of biomass gasification and PV, high strung expectations by experts led to a hasty build-up of system functions, however one major change in the institutional conditions by the government made the innovation system collapse. In the case of biomass digestion in the Netherlands, the lack of vision and consistent guidance led to scattered activities within the TIS as entrepreneurs and investors were very uncertain about the course of action the government would take. In the cases of cogeneration in the Netherlands and biomass digestion in Germany, the consistent and long-term guidance lead to a build-up of an innovation system as the institutional conditions were favourable for the respective technology, so that entrepreneurs and investors dared to take risks, by setting up installations and investing in the technology.

Market formation (F5) proved to be in most cases the final trigger that leads to system growth. Very often it is one of the last functions to be addressed, after which the build-up of the system really accelerates. This point is also made in Negro (2007), where 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. Also in the case of cogeneration the formation of a market results as the final trigger to propel cogeneration from a niche to large-scale diffusion.

Resource mobilisation (F6) turned out to be relevant in each case study. Especially the financial support helped to progress the development of the innovation system. Regular and consistent investment subsidies in the German and cogeneration case allowed further technical improvements and an increase in the construction of plants.

Finally, system function a*dvocacy coalitions (creation of legitimacy / counteract resistance of change) (F7)* by lobbying proved to be of outmost importance. It is a crucial function that positively helps to align institutions to the need of emerging innovation systems. We observed that the absence of this system function is an indicator for a poorly functioning innovation system and a poor alignment between institutions and the needs of the innovation system. In the Netherlands, no strong lobby activities occurred for putting biomass digestion on the political agenda, which resulted that policy makers but also investors did not know the technology and its potential applications. This resulted that little support was provided, ignorance about the use of the technology and objection to the construction of a plant occurred. On the other side, due to repeated lobby activities by entrepreneurs and other actors, the feed-in tariff system in Germany was adapted several times until it fitted the needs of the biogas sector and provided the trigger for breakthrough. In addition the technology became more visible, which resulted that more interest and support occurred for the technology, facilitating its diffusion.

5.2 What Other Sorts of Functional Patterns Can Be Identified?

Other observations that are made across the case studies relate to the specific event sequences, 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 shows that pressure on the incumbent system to look for alternatives and expectations about novel technological trajectories often explains the start of new search processes. These forms of guidance are a much more indirect way of technology push and market demand then what 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 no 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 around 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). That is, for a technology to become reliable and profitable, long periods of trial and error are needed. By this, the Technological Innovation System needs to provide space (a niche market) and resources (investments) for entrepreneurs to experiment with and to improve the technology. However, if this time and space is not provided, than the development and diffusion of those technologies will become very problematic. In the case of gasification technology the latter occurred, as the (theoretically based) expectations were high that the technology would become efficient and profitable. However in practice the contrary occurred. The technology proved to be far more complex and unreliable than was expected. Instead of providing a trial and error period, guidance (-F4) and resources (-F6) were removed, resulting in the failure of the technology.

6 Conclusions

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.

How suitable is the set of system functions as described in Hekkert et al. (2007) to describe and analyse the dynamics of the TIS?

Our analysis not only showed that the system functions that were proposed in Hekkert et al. (2007) are the right ones but that all of them matter. By allocating the events to each system function we could determine whether one of the system functions is superfluous or whether a system function is missing. 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. We deduced from the general development and diffusion of the Technological Innovation System studied, that knowledge diffusion occurred if there was a high diffusion of the technology, whereas little knowledge diffusion occurred when the technology was hardly diffused.

Further 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.

What do functional patterns tell us about the dynamics of Technological Innovation Systems and what sort of functional patterns can be identified?

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 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.

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 required to expand the empirical cases to different sectors and technologies.

References

[1] Albert, M. and S. Laberge (2007). "The Legitimation and Dissemination Processes of the Innovation System Approach: The Case of the Canadian and Quebec Science and Technology Policy." Science Technology Human Values %R 10.1177/0162243906296854 32(2): 221-249 March 1, 2007

[2] Bergek, A. (2002). "Shaping and Exploiting Technological Opportunities: The case of Renewable Energy Technology in Sweden." Department of Industrial Dynamics.

[3] Carlsson, B. and S. Jacobsson (2004). Dynamics of Innovation Systems - Policy-making in a Complex and Non-deterministic World. Paper presented at the 'Internation workshop on Functions of Innovation systems' at the University of Utrecht. Cleveland, Ohio; Gothenburg, Sweden, Weatherhead School of Management, Case Western Reserve University; RIDE, IMIT and Department of Industrial Dynamics, Chalmers University of Technology.

[4] Carlsson, B. and R. Stankiewicz (1991). "On the nature, function and composition of technological systems." Journal of Evolutionary Economics(1): 93-118

[5] Edquist, C. (2001). The Systems of Innovation Approach and Innovation Policy: An account of the state of the art. DRUID, Aalborg.

[6] Edquist, C. (2004a). The Systemic Nature of Innovation. Systems of Innovation - Perspectives and Challenges. Fagerberg/Mowery/Nelson. Oxford.

[7] Edquist, C. and B. Johnson (1997). Institutions and Organizations in Systems of Innovation. In Edquist, C. (ed.): Systems of Innovation - Technologies, Institutions and Organizations. C. Edquist. London, Pinter Publisher: 41-63.

[8] Freeman, C. (1987). Technology policy and economic performance - Lessons from Japan, Pinter.

[9] Galli, R. and M. Teubal (1997). Paradigmatic Shifts in National Innovation Systems. In Edquist, C. (ed.): Systems of Innovation - Technologies, Institutions and Organizations. C. Edquist. London, Pinter: 342-370.

[10] Hekkert, M. P., R. Harmsen, et al. (2007). "Explaining the rapid diffusion of Dutch cogeneration by innovation system functioning." Energy Policy 35(9): 4677-4687

[11] Hekkert, M. P., R. A. A. Suurs, et al. (2007). "Functions of Innovation Systems: A new approach for analysing technological change." Technological Forecasting and Social Change 74(4): 413-432 May 2007

[12] Jacobsson, S. and A. Bergek (2004). "Transforming the energy sector: the evolution of technological systems in renewable energy technology." Industrial and Corporate Change 13(5): 815-849 October 1, 2004

[13] Jacobsson, S. and A. Johnson (2000). "The diffusion of renewable energy technology: an analytical framework and key issues for research." Energy Policy 28(9): 625-640 2000/7/31

[14] Johnson, A. (1998). Functions in Innovation System Approaches. Sweden, Chalmers University of Technology.

[15] Johnson, A. and S. Jacobsson (2000). Inducement and Blocking Mechanisms in the Development of a New Industry: the Case of Renewable Energy Technology in Sweden. Technology and the Market. Demand, Users and Innovation. R. Coombs, K. Green, A. Richards and V. Walsh. Cheltenham, Edwar Elgar Publishing Ltd: 89-111.

[16] Liu, X. and S. White (2001). "Comparing Innovation Systems: a framework and application to China's transitional context." Research Policy 30(7): 1091-1114 2001/8

[17] Lundvall, B.-A. (2002). "Editorial." Research Policy 31: 185-190

[18] Negro, S. O. (2007). "Dynamics of Technological Innovation Systems - The case of biomass energy." Innovation Studies.

[19] Negro, S. O., M. P. Hekkert, et al. (2007). "Explaining the failure of the Dutch innovation system for biomass digestion--A functional analysis." Energy Policy 35: 925-938

[20] Negro, S. O., R. A. A. Suurs, et al. (2008). "The bumpy road of biomass gasification in the Netherlands: Explaining the rise and fall of an emerging innovation system." Technological Forecasting and Social Change 75(1): 57-77

[21] Poole, M. S., A. H. van de Ven, et al. (2000). Organizational Change and Innovation Processes, theories and methods for research. New York.

[22] Rickne, A. (2001). Assessing the Functionality of an Innovation System. Goteborg, Chalmers University of Technology.

[23] Sabatier, P. A. (1988). "An Advocacy Coalition Framework of Policy Change and the Role of Policy-Oriented Learning Therein." Policy Sciences 21(2-3): 129-168

[24] Sabatier, P. A. (1998). "The advocacy coalition framework: revisions and relevance for Europe." Journal of European Public Policy 5(1): 98-130

[25] Sabatier, P. A. and H. C. Jenkinssmith (1988). "Policy Change and Policy Oriented Learning - Exploring an Advocacy Coalition Framework - Introduction." Policy Sciences 21(2-3): 123-127

[26] Schot, J., R. Hoogma, et al. (1994). "Strategies for shifting technological systems - The case of automobile system." Futures 26(10): 1060-1076

[27] Suurs, R. A. A. and M. P. Hekkert (2007). "Cumulative Causation in the Formation of a Technological Innovation System: Biofuels Development in the Netherlands." Working Paper /Innovation Studies Utrecht (ISU) /working paper series

[28] Van de Ven, A. H. (1990). "Methods for Studying Innovation Development in the Minnesota Innovation Research Program." Organisation Science 1(3): 313-335

[29] Van de Ven, A. H., D. E. Polley, et al. (1999). The Innovation Journey, Oxford University Press.