Development paths for emerging innovation systems: implications for environmental innovations

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Abstract
The functions of innovations systems approach states that in order for an innovation system to function well several key process or functions have to be addressed. Earlier contributions on this topic provide empirical descriptions of innovation systems over time and present analyses of how the key activities fluctuate over time. This body of literature shows that there are considerable differences between function fulfillments in different innovation systems making it difficult to directly compare innovation systems. In this paper we present a first step towards such a more theoretically based approach by describing how innovation system ideally functions over time and then use this approach to analyze 17 case studies of technological innovation systems regarding environmental innovations in the Netherlands. More specifically, we describe desirable patterns of function fulfillment over the lifecycle of a technological innovation system, thereby focusing on the transition from the exploratory phase to the growth phase. We then compare these theoretical patterns to assess 17 technological innovation systems concerning environmental technologies. Outcomes show that environmental innovations in general follow similar patterns to mostly market-driven innovations but that some key processes remain unaddressed. This leads to important insights for policymakers.

Keywords: environmental innovations, technological innovation systems

1. Introduction
Innovation is a collective achievement that resides not only in the innovating firm but also in the construction of an innovation system that facilitates and constrains innovation (Van de Ven, 1999). An innovation system can be defined as all these institutions and economic structures that affect the rate and direction of technological change in society (Edquist and Lundvall, 1993). We use the term technological innovation system when the analysis focuses on the diffusion of a specific technology. Especially when the traditional direction of innovation is left and radical innovations are being developed, innovations cannot fall back on an innovation system that is already in place. The innovation system that specifically facilitates such a radical innovation needs to be build up. Therefore, these innovations require greater development time and have greater a chance of failure (Van de Ven, 1999, p. 171) Environmental innovations for long have been such a category of innovations that are not aligned with existing innovation system and require the formation of a new innovation system. The successful build up of innovation systems is essential as the time, cost and risk related to developing an innovation are inversely related to the developmental progress of building an innovation system for new technology (Rappa 1989). Existing regulation is optimally aligned with incumbent technologies and not with the environmental innovations; markets for environmental innovations are absent and within the knowledge base not much attention is paid to this type of innovations. Consequently, only few entrepreneurs dare to start a business within these boundary conditions. In recent years innovation systems for many environmental innovations have been build up to some extent, but still large scale development and diffusion of environmental technologies is not taking place as rapidly as many policy plans aim for. Thus in order to increase the diffusion of environmental innovations we need insight in successful development paths of innovation systems. Recent contributions to the literature on innovation systems focus specifically on this issue. They focus on key processes that need to take place in innovation systems in order for innovation systems to build up. The analysis of these key processes - also labeled as functions of innovation systems - provides valuable insights in the dynamics and performance of innovation systems (Jacobsson Johnson 2000, Bergek et al 2007, Hekkert et. al. 2007;
Markard and Truffer 2008). Earlier contributions on this topic provide empirical descriptions of innovation systems over time and present analyses of how the key activities fluctuate over time (Suurs 2009; Negro 2008; Hekkert et al. 2007). This body of literature shows that there are considerable differences between function fulfillments in different innovation systems making it difficult to directly compare innovation systems. But as the nature of this research is mostly descriptive it is difficult to explain the observed differences. Edquist (2005) suggest that more theoretically based empirical work is necessary to strengthen the innovation systems approach. In this paper we make a first step towards such a theoretical basis by describing how innovation system ideally functions over time and then use this approach to analyze 17 case studies of technological innovation systems regarding environmental innovations. The urgency of such a step towards theory development is particularly important (Eisenhardt 1999) since the approach was also taken up by policy makers in different countries (Bergek et al. 2005; Hekkert et al. 2008). So, even though many empirical studies on innovation system functioning have been published, what is missing is a bench mark. What type of key processes can be expected in different phases of innovation system build up? Insights in the expected patterns of function fulfillment would allow us to evaluate innovation system functioning with respect to the phase of development of the system and provides useful insights for policymakers.

The aim of this paper is to construct such general patterns of evolution for each of the functions of the innovation system using the existing literature on innovation systems and technological change as a point of departure. More specifically, we focus at a description of desirable patterns of function fulfillment over the lifecycle of a technological innovation system. Thereby we specifically address the changes that are necessary when transgressing from one stage to the next. We are especially interested in the transgression from the early stage of innovation system build up (exploratory or formative stage) to the growth phase. A particular point of interest at the beginning of this growth phase is the moment of take-off, that is the point where the system has gained momentum and from which point onwards it is very difficult to stop the diffusion process (Rogers 1962). Sometimes this point of take-off is also labeled as a separate phase in the development process of innovation systems (Geels 2002). The final phase (mature phase) is of less interest to us since many of the innovation failures take place in the exploratory and early growth phase.

Several authors have indicated that an innovation system changes, both in structure and in functionality, as it progresses through the life cycle (Bergek et al 2005, Jacobsson and Bergek 2004). Previous research has also shown that there are strong interdependencies and feedbacks between innovation structure and functioning (Alkemade et. al 2007, Hekkert et al 2007, Markard and Truffer 2008). In this paper we seek to describe the general patterns of change for both innovation system structure and functioning and compare these theoretical patterns to the actual patterns of development observed in case studies of the diffusion of environmental innovations in the Netherlands.

More specifically, in this paper we use the theoretical patterns to assess 17 technological innovation systems concerning environmental technologies in the Netherlands. The data on these technological innovation systems was compiled in evaluation exercise commissioned by the Dutch ministry of economic affairs (Hekkert et al. 2008). The patterns observed in reality will be compared to the theoretical patterns with the aim to better understand observed strengths and weaknesses of these systems.

In Section 2 we describe the theoretical concepts that form the basis of this paper. Then, in Section 3 we describe the general patterns of change for innovation system structure while Section 4 describes the expected patterns for each of the functions of the innovation system as identified in Hekkert et. al (2007). In Section 5 we compare the observed patterns to patterns observed in case studies of actual TSIS in order to determine their state of development and performance followed by conclusions and discussions in Section 6.

2. Theoretical background

Functions of Innovation Systems

The concept of innovation system is a heuristic attempt developed to analyze all societal subsystems, actors, and institutions contributing in one way or the other, directly or indirectly, intentionally or not, to the emergence or production of innovation (Nelson and Nelson, 2002). The central idea behind the innovation systems approach is that innovation and diffusion is both an individual and a collective act (Edquist, 2001). The innovation systems approach encompasses individual firm dynamics, as well as particular technology characteristics and
adoption mechanisms. Determinants of technological change are not only to be found within the individual firm but also in the innovation system. An innovation system can be defined as all these institutions and economic structures that affect the rate and direction of technological change in society (Edquist and Lundvall, 1993). Or as Freeman (1987) has put it: an innovation system is “The network of institutions in the public and private sectors whose activities and interactions initiate, import, modify and diffuse new technologies”. Jacobsson and Johnson (2000), Hekkert et. al. (2007) and Rickne (2000) have defined basic functions that need to be served in a technological innovation system in order to build up. We follow Hekkert et. al. (2007) in describing the functions of innovation systems and below we will give a short description of each function.

**Function 1: Entrepreneurial activities**
Entrepreneurs are essential for a well functioning innovation system. The role of the entrepreneur is to turn the potential of new knowledge, networks and markets into concrete actions to generate - and take advantage of - new business opportunities (Carlsson and Stankiewicz, 1991). Entrepreneurs can be new entrants that have the vision of business opportunities in new markets, or incumbent companies who diversify their business strategy to take advantage of new developments. Entrepreneurs are very important in overcoming the uncertainties which are present in the early stage of development of a new technology.

**Function 2: Knowledge development**
Mechanisms of learning are at the heart of any innovation process. For instance, according to Lundvall (1992) “the most fundamental resource in the modern economy is knowledge and, accordingly, the most important process is learning”. Many scholars such as Hekkert et. al. (2007), Jacobsson and Bergek (2004), and Johnson (2001), have recognized the importance of knowledge creation for the innovation process. Therefore R&D and knowledge development are prerequisites within the innovation system. This function encompasses ‘learning by searching’ as well as ‘learning by doing’ (Arrow, 1962).

**Function 3: Knowledge exchange**
According to Carlsson and Stankiewicz (1991) 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 in society. This function includes activities that facilitate interaction between organizations. The focus of this function lies on knowledge transfer and the accessibility of knowledge and resources. Important actors for learning by interacting are the intermediaries who act as brokers between organizations in the system. A good example of an intermediary organization is a branch organization. Furthermore, the government is crucial in assuring and supporting the flow of knowledge between public research and the commercial sector.

**Function 4: Guidance of the search**
Technological change is often guided by current problems encountered (Rosenberg 1976), and the direction of the search for solutions is determined by the technological paradigm. Since resources are almost always limited, it is important that, when various different technological options exist, specific foci are chosen for further investments. Without this selection there will be insufficient resources left over for the individual options. This guidance is given by expectations concerning the performance of the new technology, expectations concerning the ability of the innovation to contribute to solving societal problems and in a more formal sense through standard setting and regulatory processes.

**Function 5: Market formation**
New technology often has difficulty to compete with embedded technologies. Rosenberg (1976) puts it like this: ‘Most inventions are relatively crude and inefficient at the date when they are first recognized as constituting a new innovation. They are, of necessity, badly adapted to many of the ultimate uses to which they will eventually be put; therefore, they may offer only very small advantages or perhaps none at all, over previously existing techniques. Diffusion under these circumstances will necessarily be slow’. Therefore it is important that
niche markets are created to facilitate learning processes and create the circumstances for the innovation to go through the learning curve (Neij, 1997).

**Function 6: Resources mobilization**

Resources, both financial and human capital, are necessary as a basic input to all the activities within the innovation system. For a specific technology, the allocation of sufficient resources is necessary to make knowledge production possible. Jacobsson and Bergek (2004) and Johnson (2001) emphasize competence and capital as the most important resources for innovation. An important group of actors in creating financial resources to tackle a problem or to explore technological opportunities is the venture capital industry. In the field of environmental innovations also governments are an important supplier of financial resources. When human resources or competences are concerned, a well functioning educational system is of crucial importance. When radical new innovation directions are pursued a well trained labor force needs to be build up.

**Function 7: Creation of legitimacy**

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 to this force of creative destruction. In that case, advocacy coalitions can function as a catalyst; they put a new technology on the agenda (f4), lobby for resources (f6) and favorable tax regimes (f5) and by doing so create legitimacy for a new technological trajectory (Sabatier:1988). If successful, advocacy coalitions grow in size and influence and may become powerful enough to lead to creative destruction. The scale and successes of these coalitions are directly dependent on the available resources (f6) and the future expectations (f4) associated with the new technology. Stakeholders in the technological innovation system thus have to actively create and maintain legitimacy (Van de Ven 1999).

**The life cycle of a technological innovation system**

Potentially a new technological innovation system or technological system (Markard and Truffer 2008) is formed around each new technology. Important questions here are when the group of actors supporting the new technology becomes an innovation system and how this process of growth unfolds.

Different approaches make the distinction between systems in an early phase of development and more mature systems (Klepper 2007; Winter et al 2003; Malerba 2006). The multilevel model of technological change places systems in an early or formative phase of development at the niche level (Geels 2002; Geels and Kemp 2007). Whereas the regime level in the multilevel model corresponds to more mature already successful innovation systems in the fast growth and mature phases of the life cycle. Markard and Truffer (2008) furthermore consider systems in the mature phase of the life cycle as production systems rather than innovation systems. In this paper we will follow Klepper (1997) in distinguishing between an exploratory phase, an intermediate or growth phase and a mature phase in the development of a technological innovation system. We are especially interested in the transgression from the early stage of innovation system build up (exploratory or formative stage) to the growth phase. A particular point of interest at the beginning of this growth phase is the moment of take-off, that is the point where the system has gained momentum and from whereon it becomes very difficult to stop the diffusion process (Rogers 1962). Sometimes this point of take-off is also labeled as a separate phase in the diffusion process (Geels 2002).

**3. The evolution of the structure of an innovation system over time**

In this section we describe the specific processes that contribute to the fulfilment of the functions of the innovation system over time. We thereby distinguish between processes that are important in the different phases of the life cycle of a technological innovation system.

In the exploratory phase a new technological innovation system arises through the occurrence of new technologies either from science, market entry by new entrepreneurs or through diversifying activities of incumbents.

When science is an important driver for technological change, the new technology is often developed in specific niches within in the science community during long periods of time. By creating expectations about the potential future performance of the new technology, scientists are able to attract resources (often government supported) that are necessary for further
development. In this phase a number of scientists become strong advocates of the technology in question. Their prime role in the innovation system is the development of the technology and the creation of legitimacy in order mobilize the necessary resources (Suurs 2009). The exploratory phase thus sometimes includes a long R&D phase.

Several authors emphasize the role of new entrants in this phase. When an innovation has the potential to replace the dominant technology incumbents have little incentive to stimulate that technology. Cristensen (1994) also states that large incumbent firms do not possess the capabilities to successfully explore niche markets, both because their competencies are geared towards supporting the old technology, which is in a different stage of development, and because these small niche markets are not that attractive to large firms. Constant (1984) furthermore states that innovation is fostered by a new entrant position which allows for risk taking; incumbents are less likely to take these risks than new entrants (Constant 1984). System builders in the early phase of development are thus often inventor entrepreneurs who are relatively independent of the currently dominant technology.

In a system in the exploratory phase an important actor group that is specific to the system is formed by the entrepreneurs who take a risk in bringing the new technology to the market. These entrepreneurs have many characteristics of so-called Schumpeterian entrepreneurs (Dosi, 1982); they fulfill a whole range of activities in order to make their technology successful, thereby contributing to several of the functions of the innovation system. In this stage it is relevantly easy to enter the market (Klepper 1997). Since market volume is low in this phase there is only limited involvement of users. Typical users in early markets are early adopters such as technology enthusiasts and visionaries (Rogers 1962; Moore 1999). The role of the government is often limited in this phase since the technology has not yet stabilized in terms of design. This is also a reason why we do not expect innovation system specific institutions to arise in this phase. As the existing institutions have co-evolved with the incumbent technology it is often difficult for the emerging system to align with its institutional environment, especially in the case of radical innovations or disruptive technologies. However, when the new technology is considered desirable from a social welfare perspective the government may decide to stimulate the development of the new technology through R&D subsidies. Networks in the exploratory phase are often limited to the personal networks of the inventor entrepreneurs (Gilsing and Nooteboom 2006).

Summarizing in the early growth phase we expect a small innovation system were scientist and inventor entrepreneurs are the only system-specific actors and no innovation system specific institutions have evolved yet.

In the growth phase, market volumes see a sharp increase (Klepper 1997), this indicates increased opportunities for users and other actors to become involved. A shake-out among producers may occur as the product design stabilizes and some producers are able to achieve economies of scale producing the dominant design. Furthermore this is also the phase were the governmental or political subsystem becomes more involved, in its capacity as a regulator (standard setting etc). That is, innovation system-specific institutions are formed.

The system will thus grow larger and increasingly complex in terms of actors and linkages (Etzioni 1963). As the system matures additional actors will enter and specialization takes place, that is other types of actors will enter the innovation system, for example actors that focus and specialize with respect to one of the functions. The rise of intermediaries as system builders is associated with this phase (Dosi, 1988). As more specialization occurs the number and type of interactions (the formal and informal networks) between actors become increasingly important. Whereas in the exploratory phase networks were mostly informal, the growth phase is characterized by the emergence of more formal networks. It is however that the growth of the system is balanced, i.e., that the system will not be dominated by a specific actor group in this phase (Alkemade et al 2007, Meijer and Hekkert 2007). Growth in this phase is conditional upon the presence of institutions that embody the social, economic, and political infrastructure of the technological innovation (Thirtle and Ruttan, 1987).

Summarizing in the growth phase, we expect the number of entrepreneurs to decrease together with an increase in size. Furthermore, we expect other types of actors to enter the system such as intermediaries and specialized suppliers. The role of users becomes more
important in this period and networks between the different types of actors become increasingly important. Furthermore, innovation system specific institutions emerge.

Finally in the mature phase growth seizes and the innovation system turns into a production system (Markard and Truffer, 2008). In this phase institutions are perfectly aligned with system needs and the number of actors involved does not increase any further.

4. The evolution of the functions of the innovation system over time

In this section we describe expected function fulfillment in each of the three stages of development.

The exploratory phase.

Function: entrepreneurial activities: The exploratory phase is sometimes preceded by a long R&D phase especially in the case of high-tech products. Although sometimes entrepreneurs are already present in this phase it is often dominated by subsidized public R&D. The exploratory phase itself is characterized by entrepreneurial activities performed by so-called Schumpeterian entrepreneurs or diversifying activities from incumbents. First this entrepreneurial activity takes the form of applied R&D by a pioneer or research group, soon followed by an R&D race between actors with competing technological designs (Lippman and McCardle, 1987). At this stage it is relatively easy to enter the market which leads to an increase in entrepreneurial activities. This stage is characterized by competition between the new and the old technology as well as by competition between different alternative new technologies (Anderson and Tushman 1990).

Function: Knowledge development in the exploratory phase is characterized by product innovation and the search for a working prototype (learning by searching). Tacit knowledge plays an important role in this phase as uncertainties are large and the number of actors involved is relatively small. Contributions to knowledge development in this phase can be measured by the number of R&D projects, the number of patents and the investments in R&D. In terms of the outcomes of knowledge development in this phase, we would expect a variety of competing designs to be present on the market as no dominant design has been established yet.

Function: Knowledge exchange As the exploratory phase is characterized by tacit knowledge and personal networks, knowledge exchange is limited. However signaling by means of working prototypes and patent applications is an important form of strategic knowledge diffusion in this phase. Knowledge exchange is often confined to the domain of science in this phase and can be measured by the number of workshops, conferences and research collaborations devoted to a specific technology topic.

Function: guidance of the search. In the exploratory phase the guidance of the search function is addressed through processes of expectation formation, both general and specific. General expectations arise about the possible benefits of the new technology. These general expectations often arise from a sense of urgency regarding current technological or societal problems. In the case of sustainable technologies, the general goal of a sustainable future often guides the technological trajectory. Research groups create expectations about a new technology that are in line with these societal goals. Foresight studies and government plans can play an important role in creating expectations regarding innovations. Such expectations may be very high (hype cycle characteristics) in the exploratory phase and as a reaction incumbents may actively voice negative expectations about the new technology. Opinion leaders play an important role in expressing expectations about the new technology in this phase (Rogers 1962). Since the performance criteria of the technology are still unclear in this phase (Utterback 1996) expectations often are general e.g., the hydrogen economy. The occurrence of a first working prototype provides important guidance to all firms in the race that at least one of the technological trajectories is feasible and that expectations can be realized. With the realization of such a prototype expectations become more specific addressing possible features of a dominant design. Expectations are off course also influenced by the performance/expectations regarding competing technologies (Abernathy...
and Clark 1985). Expectations in the exploratory phase thus often exhibit hype cycle dynamics with alternating periods of very positive and very negative expectations.

Function: market formation. Market formation is usually limited in this early development phase as a dominant design that also defines the potential market has not yet been established and restricted to small pre-commercial markets. In this phase only early adopters – a small and innovative subgroup of the potential market (Rogers 1962) – is willing to adopt the innovation as these early innovations are often very expensive and have low performance compared to the incumbent technology (Rosenberg 1976). However, protected market niches may be created in this phase so the technology can develop, a series of such niche markets can act as a bridge to mass markets (Andersson and Jacobsson, 2000, Geels 2002). The government plays a crucial role in creating a niche market, because it holds the power to change legislation and because it can act as a ‘launching customer’. The government can articulate demand for a new technology by acting as an early user or by formulating policy targets. Furthermore, demonstration effects by a working prototype may create market interest.

Function: resources mobilization
Examples of this activity are funds made available for long term R&D programs set up by industry or government to develop specific technological knowledge and funds made available to allow testing of new technologies in niche experiments. Human resources are difficult to find since the whole process of knowledge build up and specific education is still in its infancy.

Function: creation of legitimacy. Legitimation is an important issue in the exploratory phase (Van de Ven 1999). Sources of legitimacy for a new technology can be exogenous as is often the case with environmental technologies. In this case legitimacy is created by a general societal concern or sense of urgency. This societal problem delegitimizes the incumbent technology and thereby provides general legitimacy for the new technology. But legitimacy is also often endogenous when large diffusion, high quality and consumer trust provide legitimacy for the technology (Van de Ven 1999). In this later case positive technological expectations and product performance are aligned which provides legitimacy. Of course incumbents strategically may strategically raise doubts about legitimacy new technology and low product quality and consumer trust will raise legitimacy issues.

The growth phase
Function: entrepreneurial activities. Entrepreneurial activities in this phase are characterized by building production capacity, process innovation, specialization and the exploitation of economies of scale. These highly capital intensive processes can lead to a decrease in the number and variety of entrepreneurial activities due to shake-outs and industry consolidation. This phase starts with the occurrence of a dominant design (Suarez and Utterback 1995) which causes standards to come into place (either as a defacto standard = dominant design) or by means of regulation. The early growth phase is the most risky phase in the life cycle of an innovation system. Uncertainties are high and the necessary investments are also very high. This is a very difficult phase for entrepreneurs where many do not succeed (valley of death).

Function: knowledge development. In this phase is characterized by knowledge accumulation. Knowledge is increasingly codified as production volumes increase and the emphasis is on process innovation. The incorporation of user knowledge plays an important role in this phase (learning by doing).

Function: knowledge exchange. As this phase is characterized by codified knowledge diffusion becomes easier. Firms may also strategically diffuse knowledge concerning their technology in order to influence the process of standard setting. Also user-producer interaction is an important form of knowledge exchange in this phase.

Function: Guidance of the search. Expectations become increasingly specific at this stage where a dominant design arises. Other important forms of guidance in this phase may come from standard setting and regulatory processes in this phase. Political dynamics drive industry
standards and the consequences of these standards for subsequent technological evolution (David 1987, Hughes 1987). As a result we observe a convergence of expectations; that is expectations become increasingly shared.

Function: Market formation. Market volumes for successful innovations grow in this phase due to increased performance and decreasing in price as a result of technological learning. For environmental technologies this is often not the case without government support. Specific tax regimes for new technologies and new (environmental) standards that improve the chances for new environmental technologies are examples of measures that are taken to stimulate market formation. Market formation often proceeds through a series of niche markets (encompassing early adopters or created through favorable legislation) before mass market diffusion is reached.

Function: Resources mobilization. The increased production volumes require considerable investments of financial resources. These resources are expected to be provided by profit oriented actors such as venture capitalist or capital intensive incumbents that diversify or buy entrepreneurial firms. In the early growth phase where uncertainties are very high, this is a problematic activity. In later growth phases, uncertainty decreases and the availability of capital increases. Specialized and skilled labor is difficult to find in early growth phases while in later phases this problem decreases.

Function: Creation of legitimacy. Ideally, legitimacy issues have been resolved in this phase before up scaling begins. Function fulfillment in this phase is often done by dedicated interest and lobby groups such as branche organizations and NGO’s that lobby to advance the technology.

The mature phase
Function: Entrepreneurial activities The innovation system by now has more characteristics of a production system (Markard and Truffer 2008). The number of entrepreneurs remains stable or decrease and the focus of activities shift from product or process innovation to marketing and advertising to defend market shares.

Function: knowledge development Knowledge is usely considered adequate in this phase with an emphasis on business knowledge rather than technological knowledge.

Function: knowledge exchange knowledge is considered widely available.

Function: guidance of the search. There is a good match between expectations and product performance in this phase. The direction of technological trajectory is clear in this phase.

Function: Market formation. This phase is characterized by market saturation or eroding markets due to new competitors

Function: Resources mobilization. Resources are not considered problematic in this phase and resources are increasingly deployed towards marketing and advertising.

Function: Creation of legitimacy. Legitimacy may become an issue again in the mature phase when new competing technologies enter the market.

As this paper focuses on the changes in innovation system dynamics that are expected as the system moves from the exploratory to the growth phase we provide a short summary of the processes that are identified above for each function in these two phases:
Table 1: Dominant forms of function fulfillment in each phase.

<table>
<thead>
<tr>
<th>Function</th>
<th>Exploratory phase</th>
<th>Growth phase</th>
</tr>
</thead>
</table>
| F1: Entrepreneurial activities | Experimentation with different designs  
                                | Competition between alternative designs  
                                | High entry/growth in number of entrepreneurs | Specialization  
                                | Shake out |
| F2: Knowledge development | Learning by searching  
                                | Product innovation                  | Learning by doing  
                                | Process innovation |
| F3: Knowledge exchange | Exchange through personal networks  
                                | Exchange at academic conferences  
                                | Science – entrepreneur interaction | User producer interaction |
| F4: Guidance of the search | Hype cycle expectation dynamics  
                                | Expression of general positive expectations  
                                | Appearance of foresight studies and government plans | Expression of more realistic and specific expectations  
                                | Technology Standards |
| F5: Market formation | Limited demand articulation  
                                | Small non commercial market for experimenting | Creation of niche markets  
<pre><code>                            | Establishment of mass markets |
</code></pre>
<p>| F6: Resources mobilization | Availability of (Public) R&amp;D funds  | Availability of capital from profit oriented actors |</p>
<table>
<thead>
<tr>
<th>F7: Creation of legitimacy</th>
<th>Alignment with general societal concerns</th>
<th>Lobbying by dedicated lobby groups, branche organizations and NGO’s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Alignment with positive expectations</td>
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</table>

5. Comparison to actual patterns

For our analysis we compare the literature based patterns derived in Table 1 to the patterns actually observed in a policy review involving 17 case studies of technological innovation systems concerning sustainable energy and energy efficient innovations in the Netherlands. Comparing the actual patterns to the theoretical patterns will provide us with insights regarding the question whether environmental-innovations follow different patterns than innovations that are predominantly market driven. Furthermore the comparison will hopefully provide us with more insights regarding the strengths and weaknesses of the different innovation systems and the underlying dynamics that cause these differences. In the remainder of this section we will first describe the data and the method that was used to gather the data. Then we will show how these patterns compare to the patterns from Table 1.

**The data**

In the Netherlands, the transition towards a more sustainable transportation society takes place in the context of the Dutch “Transition management policy framework”. Within this framework about 30 so-called transition paths were identified that can contribute to the transition of the energy system to a more sustainable energy system. An example of such a transition path is the use of hydrogen as a transport fuel. Several of these transition paths encompass the implementation of so-called environmental innovations. In 2008 the authors have contributed to an evaluation of the technological innovations system of all these paths with the aim to provide policymakers with the necessary inputs for stimulating the transition. This study was commissioned by the Dutch ministry of economic affairs.

In this study we have thus performed an innovation systems analysis of all transition paths that encompass the development of new technology as a means to achieve a more sustainable energy system. The necessary data was collected through group interviews with experts.

In each analysis the experts were asked to describe and determine (1) the phase of development of the system, (2) the key actors and their interactions, (3) the functioning of the system. In order to evaluate system functioning actors were asked to describe how the functions of the innovation system as described in Section 4 above were fulfilled and subsequently to rate this performance on a 5 point Likert scale (very weak – very strong). Furthermore, the experts were asked to describe the most important barriers within the system and to describe the possible policy implications of these barriers. In this paper we have used the records of these interviews to analyze whether the key processes as described in Table 1 were present in each of the systems.

Before we present the results of our analysis we first give a general overview of the outcomes of the analysis in Tables 3 and 4. First Table 2 gives an overview of all the technological innovation systems that were evaluated, including an indicator of the phase of development of the system as indicated by the expert groups.

Table 2 shows some interesting aspects regarding the classifications of the expert panel. The experts have indicated whether the technology was in the exploratory phase (including R&D), the early growth phase (before take-off) or the growth phase (after take-off). It is interesting to notice that the technologies that were placed in the growth phase are indeed do have a working prototype and limited diffusion, but industrial combined heat and power technology
(CHP) is the only technology that already has a substantial market share. Of the technologies that were placed in the exploratory phase by the experts some technologies are clearly in the R&D stadium whereas other technologies already have a working prototype but do not succeed in reaching the take-off point. Below we will further analyze these differences by examining to what extent the key processes of function fulfillment are present for each technology. The results of this analysis are presented in Table 3.

Table 2: Overview of the technological innovation systems and their phase of development.

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Technology</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Aquatic biomass</td>
<td>Exploratory</td>
</tr>
<tr>
<td>2</td>
<td>Crops for biorefining</td>
<td>Exploratory (R&amp;D)</td>
</tr>
<tr>
<td>3</td>
<td>Sustainable biofuels</td>
<td>Growth</td>
</tr>
<tr>
<td>4</td>
<td>Hydrogen as a transport fuel</td>
<td>Exploratory</td>
</tr>
<tr>
<td>5</td>
<td>Natural gas as a transport fuel</td>
<td>Growth</td>
</tr>
<tr>
<td>6</td>
<td>Green gas: vergisting</td>
<td>Exploratory</td>
</tr>
<tr>
<td>7</td>
<td>Green gas: SNG from biomass</td>
<td>Exploratory (R&amp;D)</td>
</tr>
<tr>
<td>8</td>
<td>Micro CHP</td>
<td>(early) growth</td>
</tr>
<tr>
<td>9</td>
<td>CHP</td>
<td>Growth</td>
</tr>
<tr>
<td>10</td>
<td>Hybrid vehicles</td>
<td>(early) growth</td>
</tr>
<tr>
<td>11</td>
<td>Compact heat storage</td>
<td>Exploratory (R&amp;D)</td>
</tr>
<tr>
<td>12</td>
<td>Solar heating</td>
<td>Growth</td>
</tr>
<tr>
<td>13</td>
<td>Carbon capture and storage</td>
<td>(early) growth</td>
</tr>
<tr>
<td>14</td>
<td>Photovoltaic technology</td>
<td>Exploratory</td>
</tr>
<tr>
<td>15</td>
<td>Geothermal heat</td>
<td>(early) growth</td>
</tr>
<tr>
<td>16</td>
<td>Onshore wind energy</td>
<td>Growth</td>
</tr>
<tr>
<td>17</td>
<td>Offshore wind energy</td>
<td>(early) growth</td>
</tr>
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Table 3: Observed processes in the different systems.

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<thead>
<tr>
<th>Exploratory phase (as indicated by expert group)</th>
<th>1</th>
<th>2</th>
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<td>F1: Experimentation different designs</td>
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<td>F1: Competition alternative designs</td>
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<tr>
<td>F1: High entry/growth</td>
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<td>F2: Learning by searching</td>
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<td>F3: Scientific-entrepreneur interaction</td>
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<td>F4: General positive expectations</td>
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<td>F4: Foresight studies/gov. plans</td>
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<td>F5: Demand articulation</td>
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<td>F5: Small pre-commercial markets</td>
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<td>F6: Public R&amp;D funds</td>
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<td>F7: general societal concerns</td>
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<td>F8: alignment positive expectations</td>
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</tbody>
</table>

| Growth phase                                     | +  | +  | +  | +  |
| F1: Specialization                               | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |
| F1: Shake-out                                    | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |
When considering Table 3 several observations can be made. First we find that the patterns of function fulfillment are generally consistent with the phase of development of the systems as indicated by the expert groups. Second we notice that two processes are not present in any of the systems. These processes are the increase in entrepreneurial activities through high entry that is expected in the exploratory phase and the mass market formation that is necessary in the growth phase. Finally we notice that the availability of private or venture capital is indicated as insufficient when resources fulfillment in the growth phase is concerned. Below we will discuss the implications of each of these observations.

### 6. Interpretation of results and concluding remarks

First from the observation that the patterns of function fulfillment are generally consistent with the phase of development of the systems as indicated by the expert groups we can derive
that environmental innovations in general follow the same patterns of development as innovations that are mostly market driven. This has important implications for policymakers as it indicates that policymakers should take into account the processes that are currently not adequately addressed in formulation policy packages that aim to stimulate sustainable technologies.

When we consider the observation that the increase in entrepreneurial activities through high entry that is expected in the exploratory phase policy implications are less clear. The expert groups labeled this as very typical for environmental innovation and contributed this to the large uncertainties regarding the future governmental support of the technology (through legislation and subsidies). However high entry as is observed in many more market driven technological trajectories and the resulting competition for market share plays an important role in achieving cost reductions and performance improvements for the new technology and it is unclear whether these incentives can be successfully incorporated in subsidy regimes. Subsidizing entrepreneurial activity when technology performance does not yet meet market demand may lead to the large scale diffusion of ‘bad technology’ as was for example observed with wind energy deployment in California (Alkemade et al. 2007). It is particularly important for policymakers to be aware of these risks because the expert groups in 11 of the 17 systems under investigation suggest lack of government support for large scale experiments as the most important barrier for the technology. Our results indicate that policymakers should only move to stimulate such large scale experiments when it is possible to include a variety of competing technologies and actors in the experiment.

The observation that the mass market formation that is necessary in the growth phase is not taking place is mostly related to the state of development of the technology. Many technologies have not yet realized the cost reductions and performance reductions that are necessary for large scale diffusion. The evaluation of this performance is of course closely related to the position of the technology with respect to the incumbent technology and to (the expectations concerning) competing technologies. The absence of dedicated lobby groups for many technologies is an indicator for this observation as is the lack of financial resources from private investors and venture capital that was observed in many cases. Finally the fact that essential processes such as process innovation, specialization and user-producer interaction remain largely unaddressed in this phase is an indicator that policy should be directed towards technology improvement rather than mass market formation.

Summarizing in this paper we have elaborated on the functions of innovations systems approach that states that in order for an innovation system to function well several key process or functions have to be addressed. Earlier contributions by the authors on this topic provide empirical descriptions of innovation systems over time and present analyses of how the key activities fluctuate over time (Suurs 2009; Negro 2008; Hekkert et al. 2007). This body of literature shows that there are considerable differences between function fulfillments in different innovation systems making it difficult to directly compare innovation systems. In this paper we have presented a first step towards such a more theoretically based approach by describing how innovation system ideally functions over time and then used this approach to analyze 17 case studies of technological innovation systems regarding environmental innovations. More specifically, we described desirable patterns of function fulfillment over the lifecycle of a technological innovation system, thereby focusing on the transition from the exploratory phase to the growth phase. We then used these theoretical patterns to assess 17 technological innovation systems concerning environmental technologies. Outcomes show that environmental innovations in general follow similar patterns as mostly market-driven innovations but that some key processes remain unaddressed. This overview of fulfillment of key processes leads to important insights for policymakers.

References


1 In the analysis of technological innovations systems 1,5,6,8,9,10,12,13,15,16 and 17


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Hippel, E. von (2007). Horizontal innovation networks-by and for users. Industrial and corporate change, 16(2):293-315.


Hekkert, M.P., F. Alkemade, S.O. Negro, R. Suurs, K. van Alphen, J. Farla and R. Vandenberg. Innovatiesysteemanalyse: een methode voor het monitoren/evalueren van transitieprocessen. 2008 (In Dutch). http://soliscms.uu.nl/content/methodeUU.pdf

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