
Transforming the energy sector: the evolution of technological systems in renewable energy technology

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This paper analyses the development and diffusion of technologies that utilize renewable energy sources in Germany, Sweden and the Netherlands. The analysis enlarges the life cycle model of industry evolution to one where the focus is on the formation and evolution of new technological systems. Particular focus is on explaining success and failures in shifting from a formative phase into one characterized by positive feedbacks. A set of challenges is identified for policy makers attempting to influence the process of transforming the energy sector.

1. Introduction

Fossil fuels are the dominant source of energy in the world, contributing about 80% (91,000 TWh) of the total primary energy supply and 64% (9400 TWh) of the electricity generation in 1999. This dominance is associated with clear environmental and climate challenges. A wider use of renewable energy technology is seen as one way of meeting these challenges. For instance, the European Union aims at increasing the share of renewable energy in the supply of electricity from about 14% in 1997 to 22% by 2010 (Lauber, 2002). To obtain and surpass this share, a range of renewable energy technologies need to be diffused.

Large-scale hydropower and combustion of different types of biomass currently provide the bulk of the energy supplied from renewable energy sources. In 1999, these supplied roughly 2600 and 12,600 TWh (160 TWh of electricity; UNDP, 2000)¹ of primary energy respectively (IEA, 2001). In addition to these, the ‘new’ renewables—wind turbines, solar cells and solar collectors—are now diffusing at a quite rapid rate (see Appendix Table A1).

In the 1990s, the global stock of wind turbines increased by an average of 27% per annum, leading to an electricity supply of about 56 TWh in 2001. The stock of solar cells grew by 22% per annum in the same period, producing roughly 2 TWh of electricity in 2001, whereas the stock of solar collectors in Europe increased by 12% per annum, supplying about 6 TWh of heat in 2001.

¹These data are for 1998.

Whereas the share of these technologies in the global energy supply is marginal at present (less than 0.5% of the 15,000 TWh of electricity generated in the world), their potential is considerable. There are visions of wind power accounting for 10% of the world's electricity supply and of solar cells supplying 1% by 2020 (EWEA *et al.*, 1999; Greenpeace and EPIA, 2001). The real issue is no longer the technical potential of these (and other) renewable energy technologies, but how this potential can be realized and substantially contribute to a transformation of the energy sector. The purpose of this paper is to add to the current (energy) policy debate by synthesizing a number of studies on the development and diffusion of renewable energy technology in Sweden, Germany and the Netherlands (Andersson and Jacobsson, 2000; Jacobsson and Johnson, 2000; Johnson and Jacobsson, 2001; Bergek, 2002; Bångens and Sinhart, 2002; Bergek and Jacobsson, 2003; Jacobsson *et al.*, 2004).

Before we proceed, we need to point to three features of the energy sector that characterize the larger context in which we must place any analysis of how policy may influence the transformation process. First, the energy system is huge. Even with continued high growth rates over the next two decades, wind and solar power may only begin to replace the stock of conventional energy technologies well after 2020 (see Appendix Table A2). Yet a transformation of the energy sector post 2020 rests on a range of policy initiatives taken today and over the course of the preceding decades. Policy making must therefore be conducted with a very long-term perspective.

Second, for several reasons, markets are not easily formed. New technologies often have a cost disadvantage in comparison to incumbent technologies and they may not offer any direct benefits for the individual buyer or investor (but reduce society's costs in terms of e.g. CO₂ reduction). In addition, incumbent technologies are often subsidized. This refers not only to R&D subsidies in the past, which were substantial (Watson, 1997; Goldberg, 2000; Norberg-Bohm, 2000), but also to other forms of direct subsidies. For instance, UNDP (2000) estimates that 'conventional' energy received subsidies in the order of 250–300 billion USD yearly in the mid-1990s. Incumbent technologies are also subsidized indirectly as there are various types of negative external economies associated with the use of conventional energy technologies.² Although the size is difficult to estimate, the European Commission suggests that 'the cost of producing electricity from coal or oil would double . . . if the external costs such as damage to the environment and to health were taken into account' (Milborrow, 2002: 32). In defining the incentives for investors in renewables, policy makers must give due consideration to these direct and indirect subsidies to incumbent technologies.

Third, the proponents of the established energy system often attempt to block the diffusion of renewables by influencing the institutional framework so that it continues

²Examples of these are air pollution, which has significant negative effects on health and on the level of acidification of lakes, emission of carbon dioxide with implications for global warming and health hazards associated with mining of uranium, the use of that uranium in nuclear power plants and in the storage of residues from that process.

to be to their advantage. Indeed, the current debate over the future of the energy system involves intense lobbying over both policy goals and design of the institutional framework. Policy making is thus a highly political business.

The remaining part of the paper is structured as follows. Section 2 contains our analytical framework. Section 3 identifies the main mechanisms that have induced or blocked the diffusion of renewables. In Section 4, we turn to the dynamics of the emergence and growth of new technological systems in the energy field. The final section contains a discussion about lessons for policy.

2. Analytical framework: the evolution of technological systems

As is argued in the broader literature on innovation systems, the innovation and diffusion process is both an individual and a collective act. The determinants of this process are not only found within individual firms; firms are embedded in innovation systems that guide, aid and constrain the individual actors within them. In this manner, technical change becomes endogenous to the economic system.

The process whereby a specific new technology emerges and is improved and diffused in society may be studied using the concept of a technological system, which is a technology-specific innovation system (Carlsson and Stankiewicz, 1991; Jacobsson and Johnson, 2000).³ Due to the technology-specific features of the approach, it is particularly attractive when the focus of enquiry is competition between emerging technologies and incumbent technologies (and between the associated technological systems).

A technological system is defined as ‘network(s) of agents interacting in a specific technology area under a particular institutional infrastructure for the purpose of generating, diffusing, and utilizing technology’ (Carlsson and Stankiewicz, 1991: 21), and is made up of three main elements:

1. *Actors (and their competencies)*, which may be firms, e.g. users, suppliers or venture capitalists, or other organizations. A particularly important actor is a ‘prime mover’ or system builder (Hughes, 1983), an actor (or set of actors) that is technically, financially and/or politically so powerful that it can strongly influence the development and diffusion process. Other notable actors are non-commercial organizations acting as proponents of specific technologies. Unruh underlines the existence of a range of such organizations and the multitude of roles they play:

³Several alternative concepts are similar to that of ‘technological system’. In particular we would like to mention the concepts of ‘industry social system’ (Van de Ven and Garud, 1989), ‘regime shifts’ (Kemp *et al.*, 1998), ‘socio-technical configurations’ (Geels, 2002) and ‘industrial clusters’ (Porter, 1998). Similar thoughts are also found within the social construction of technology approach (see e.g. Garud and Karnoe, 2003).

users and professionals operating within a growing technological system can, over time, come to recognize collective interests and needs that can be fulfilled through establishment of technical . . . and professional organisations . . . These institutions create non-market forces . . . through coalition building, voluntary associations and the emergence of societal norms and customs. Beyond their influence on expectations and confidence, they can further create powerful political forces to lobby on behalf of a given technological system. (Unruh, 2000: 823)

2. *Networks* constitute important channels for the transfer of both tacit and explicit knowledge. These networks may be built around markets and may therefore be conducive to the identification of problems and the development of new technical solutions. They may also be non-market related and conducive to a more general diffusion of information or to an ability to influence the institutional set-up. Being strongly integrated into a network increases the resource base of individual actors, in terms of gaining access to the information and knowledge of other actors. Networks also influence the perception of what is desirable and possible, i.e. shape the actors' images of the future, which then guide the specific decisions of firms and other organizations.
3. *Institutions* stipulate the norms and rules regulating interactions between actors (Edquist and Johnson, 1997), and the value base of various segments in society. The roles of institutions vary; some influence connectivity in the system whereas others influence the incentive structure or the structure of demand. Institutions are important not only for the specific path a technology takes but also to the growth of new industrial clusters (Carlsson and Stankiewicz, 1991; Edquist and Johnson, 1997; Porter, 1998).

A useful way to analyse the workings of a technological system is to focus on how a number of functions are served in the system (Rickne, 2000; Johnson and Jacobsson, 2001). These functions constitute an intermediate level between the components of a technological system and its performance. An extensive review of the innovation system literature (Johnson, 1998; Johnson and Jacobsson, 2001) suggests that five basic functions need to be served in a technological system:

- The creation and diffusion of 'new' knowledge.
- The guidance of the direction of search among users and suppliers of technology. This function includes guidance with respect both to the growth potential of a new technology (which may be closely linked to the legitimacy of it) and to the choice of specific design approaches.
- The supply of resources such as capital and competencies.
- The creation of positive external economies, both market and non-market mediated.
- The formation of markets. Since innovations rarely find ready-made markets, these may need to be stimulated or even created. This process may be affected

by governmental actions to clear legislative obstacles and by various organizations' measures to legitimize the technology.

These functions are not independent of one another, and changes in one function may lead to changes in others (Bergek and Jacobsson, 2003). For instance, the creation of an initial market may act as an inducement mechanism for new entrants that bring new resources to the technological system.

There are two main reasons for analysing a technological system in functional terms as well as in terms of its constituent components. First, we can define the border of the system, an inherently very difficult task (Carlsson *et al.*, 2002), by analysing what promotes or hinders the development of these functions (Johnson and Jacobsson, 2001). Second, there is no reason to expect a particular system structure to be related to the performance of a technological system in a clear and unambiguous way. By arranging our empirical material in terms of functions, we can trace the way through which, for instance, a particular combination of actors or a specific institutional set-up shapes the generation, diffusion and utilization of a new technology.

For a transformation of the energy system to take place, new technological systems with powerful functions need to emerge around a range of new energy technologies. Whereas our understanding of how new technological systems evolve is limited (Carlsson and Jacobsson, 1997a; Breschi and Malerba, 2001), some insight into the roots of and regularities in the evolution of technological systems may be gleaned from the literature.

In the literature on product/industry life cycles (see e.g. Utterback and Abernathy, 1975; Van de Ven and Garud, 1989; Utterback, 1994; Klepper, 1997; Tushman *et al.*, 1997; Bonaccorsi and Giuri, 2000), it is usually possible to identify two main phases in the evolution of a product or an industry—a formative period and one of market expansion—which differ in terms of the character of technical change, the patterns of entry/exit and the rate of market growth.

With respect to the characteristics of the *formative period*, the literature emphasizes the existence of a range of competing designs, small markets, many entrants and high uncertainty in terms of technologies, markets and regulations (Afuah and Utterback, 1997; Klepper, 1997; Kemp *et al.*, 1998). However, we need to go beyond these features and understand the process in which this formative stage emerges, i.e. how all the constituent components of a technological system emerge and how the five functions begin to gain strength. We will emphasize four features of this process: market formation, the entry of firms and other organizations, institutional change and the formation of technology-specific advocacy coalitions (a particular form of network).

In the formative phase, *market formation* normally involves exploring niche markets, markets where the new technology is superior in some dimension(s). These markets may be commercial, with somewhat unusual selection criteria (Levinthal, 1998), and/or involve a government subsidy. Such 'protected spaces' for the new technology may serve as 'nursing markets' (Ericsson and Maitland, 1989) where learning processes can take

place, the price/performance of the technology be improved and new customer preferences be formed.

This protective space may not be limited to the very first niche markets—the diffusion of a new technology can be seen as an exploration of a whole series of niches prior to reaching mass markets, and protection may be required and awarded by markets that act as bridges to mass markets (Andersson and Jacobsson, 2000; Geels, 2002). Such ‘bridging markets’ allow for larger volumes of production and a series of ‘secondary innovations’, in Schmookler’s (1966) terminology, both of which may be required before the new technology can become a commodity.

The formation of nursing and bridging markets has an importance that goes beyond improving price/performance of the new technology; they generate a ‘space’ for the elements in the technological system to fall in place. In particular, by guiding the direction of search, these markets provide an incentive for the *entry of firms* into various parts of the value chain.

Firm entry may shape new technological systems in three main ways. First, each new entrant brings knowledge and other resources into the industry. Second, they enlarge the technological system by filling ‘gaps’ (e.g. by becoming specialist suppliers) or by meeting novel demands (e.g. by developing new applications). In that process, a division of labour is formed and, associated with this, further knowledge formation is stimulated by specialization and accumulated experience (see e.g. Smith, 1776; Young, 1928; Maskell, 2001).

Third, positive external economies may emerge beyond those associated with a further division of labour—a new entrant may raise the returns for subsequent entrants (and for incumbents) in additional ways. These external economies, which may be both pecuniary and non-pecuniary (Scitovsky, 1954), include Marshallian externalities (Breschi and Lissoni, 2001) but go beyond these. They may, for example, come in the form of passing of information in networks or an increased availability of complementary resources. Indeed, ‘Each successful firm . . . creates a demand for certain intermediary services such as legal and accounting services. Greater availability of these services also facilitates the start-up process for subsequent firms, and higher rates of entry of firms encourage venture capital to enter’ (de Fontenay and Carmel, 2001: 26).

New entrants may also play an important role for the process of legitimization of a new field:

The ecological theory of long-term organisational evolution posits that when a new organisational form appears, such as automobile manufacturing in the late 19th century, it lacks legitimation or social taken-for-grantedness. Low or absent legitimation implies that organizing is difficult: capital sources are wary; suppliers and customers need to be educated; employees may be hard to find and recruit; and in many instances hostile institutional rules must be changed. As the form proliferates, legitimation increases. Initially, when the number of

organizations is low, the returns to legitimation of adding another organization is great. (Carroll, 1997: 126).

The legitimacy of a new technology and its actors, their access to resources and the formation of markets are strongly related to the institutional framework. If the framework is not aligned with the new technology, several functions may be blocked. *Institutional change* (and by implication its politics) is therefore at the heart of the process whereby new technologies gain ground (Freeman, 1977, 1978; Freeman and Louca, 2002).

Institutional change, or alignment, is a multifaceted process. For example, supporting the formation of a new technological system involves a redirection of science and technology policy in order to generate a range of competing designs. This knowledge creation may have to begin well in advance of the emergence of markets, but it also needs to be sustained throughout the evolution of the system. Institutional alignment is, however, also about market regulations, tax policies, value systems, etc. that may be 'closer' to the operation of specific firms. In particular, institutional change is often required to generate markets for new technologies. The change may, for instance, involve the formation of standards.

The centrality of institutional alignment implies that firms in competing technological systems not only compete in the market for goods and services but also to gain influence over the institutional framework. As Van de Ven and Garud (1989: 210) put it, 'firms compete not only in the marketplace, but also in this political institutional context. Rival firms often cooperate to collectively manipulate the institutional environment to legitimize and gain access to resources necessary for collective survival . . .'⁴

This is well recognized in the political science literature (see e.g. Sabatier, 1998; Smith, 2000), which argues that policy making takes place in a context where *advocacy coalitions*, made up of a range of actors sharing a set of beliefs, compete in influencing policy in line with those beliefs (Smith, 2000). The political science literature looks at coalitions in a non-technology specific manner, which is reasonable considering that the political debate over, say, climate change, is not necessarily focused on specific technological systems.⁵ However, for a new technology to gain ground, *technology specific coalitions* need to be formed and to engage themselves in wider political debates in order to gain influence over institutions and secure institutional alignment. As a part of this process, advocates of a specific technology need to build support among broader advocacy coalitions, which have the strength to influence the policy agenda (Witt, 2003). These need to be convinced that a particular technology, e.g. solar cells or gas turbines, is a solution to wider policy concerns. Hence, the formation of 'political

⁴Similarly, Davies (1996) underscores the centrality of the political dimension in the competition between incumbents and contenders in his study of innovations in telecommunications.

⁵We are grateful to Dr Adrian Smith for pointing this out to us.

networks'⁶ with the objective of shaping the institutional set-up is an inherent part of this formative stage.

A coalition may include many types of organizations and actors, such as universities, private and non-commercial associations, media, politicians at different levels and elements of the state bureaucracy (Feldman and Schreuder, 1996; Porter, 1998). However, individual firms and related industry associations play an especially important role in the competition over institutions. Thus, the entry of firms into various parts of the value chain has yet another consequence for the emergence of a new technological system: the new entrants allow for the formation or the strengthening of a technology-specific advocacy coalition, which may gain enough strength to influence the institutional set-up. As mentioned earlier, such entries are dependent on the emergence of niche markets. An early formation of markets is therefore at the heart of the formative stage. As Kemp *et al.* argue:

Without the presence of a niche, system builders would get nowhere . . . Apart from demonstrating the viability of a new technology and providing financial means for further development, *niches help building a constituency behind a new technology*, and set in motion interactive learning processes and institutional adaptation . . . that are all-important for the wider diffusion and development of the new technology. (Kemp *et al.*, 1998: 184, our emphasis)

The time span involved in a formative phase may be very long. This is underlined in a recent study of Israel's 'Silicon Wadis', which began a rapid period of growth in the 1990s after a history starting in the 1970s (see de Fontenay and Carmel, 2001). This time span is not unusual; the first commercial major market for steam ships took about 50 years to materialize (Geels, 2002) and the formative stages of the US technological systems for computers and semiconductors lasted for several decades (Carlsson and Jacobsson, 1997a). Often, the investments are substantial and seemingly without success. Breshanan *et al.* summarize the lessons from a set of case studies on the evolution of ICT clusters:

Another similarity . . . is the degree of investment, effort and building needed to set up the background for an innovation cluster's take off. . . . it takes years of firm-building and market-building efforts . . . sometimes these long-term investments in national or regional capabilities can grow for a long time in what seems like a low-return mode before the take off into cluster growth . . . (Breshanan *et al.*, 2001: 843–844)

At some point, however, these investments may have generated a large enough system

⁶In the subsequent text, this term will be used synonymously with the term advocacy coalitions by which we mean technology specific ones.

which is sufficiently complete for it to be able to ‘change gear’ and begin to develop in a self-sustaining way (Carlsson and Jacobsson, 1997b; Porter, 1998).

A necessary condition for a ‘change in gear’ to take place is that larger markets are formed—the system needs to get connected to an underlying wave of technological and market opportunities (Breshanan *et al.*, 2001).⁷ As it does so, a chain reaction of positive feedback loops may materialize which involve all the constituent components and the functions of the technological system. The linkages between functions may turn out to be circular, setting in motion a process of cumulative causation.

Indeed, as pointed out long ago by Myrdal (1957), virtuous circles are central to a development process. He even suggested that ‘the main scientific task is . . . to analyse the causal inter-relations within the system itself as it moves under the influence of outside pushes and pulls and the momentum of its own internal processes’ (Myrdal, 1957: 18).

It is, however, not an easy task to unravel these causal interrelationships, or to predict how they respond to outside pushes, e.g. policy. Technological systems are dynamic and unstable, and any change in a component in the system (e.g. a new entrant or a change in the institutional set-up) may trigger a set of actions and reactions in the system (Carlsson *et al.*, 2002). Under what conditions a ‘change in gear’ will take place is therefore difficult to predict.

A process of cumulative causation can, however, only be set in motion if the technological system has gone through a formative period—without it, a response capacity to the underlying wave will not exist and, indeed, the wave itself may not be there. But, as Breschi and Malerba (2001) point out, making the required investments in the formative period is very risky. There are many reasons for expecting that the broader (not only market) selection environment is biased in favour of incumbent technological systems and that a new technological system may consequently develop very slowly or in a stunted way—a system failure may occur (Carlsson and Jacobsson, 1997b). Kemp *et al.* argue similarly that

many factors . . . impede the development and use of new technologies . . . These factors are interrelated and often reinforce each other. What we have is not a set of factors that act separately . . . but a structure of interrelated factors that feed back upon one another, the combined influence of which gives rise to inertia and specific patterns in the direction of technological change. (Kemp *et al.*, 1998: 181)

These reasons and factors are found in all components of the technological system. For instance:

⁷For example, some ICT clusters have become successful by linking up to the US market (Breshanan *et al.*, 2001), whilst the Nordic technological systems in mobile telephony grew into a second phase with the European GSM standard.

- Institutions may fail to align themselves to the new technology—this may encompass the regulatory framework or the functioning of the educational and capital markets.⁸
- Markets may not be formed due to, for instance, the phenomenon of increasing returns to adoption, which benefits established technologies, or direct and indirect subsidies to incumbent technologies.
- Additional firms may not enter due to a lack of markets or because they tend to build on their existing knowledge base when they search for new opportunities, which may restrict their search process.
- Networks may fail to aid new technology simply because of poor connectivity between actors. The proponents of the new technology may also be organizationally too weak to counteract the influence on legislation, public opinion, etc. of the vested interest groups of the incumbent technology.

Such ‘blocking mechanisms’⁹ may operate in a formative stage, but they may also obstruct a transition towards a more self-sustained technological system, i.e. one which is to an increasing extent driven by its own momentum rather than by outside ‘pushes or pulls’ in the form of policy. Clearly, we would expect powerful inducement mechanisms to be needed in order to overcome this range of potential blocking mechanisms, and we would expect the nature of both inducement and blocking mechanisms to vary between countries and technologies.

In what follows, we will first elaborate on the nature of inducement and blocking mechanisms in renewable energy technology (Section 3). We will then relate our understanding of the dynamics of system evolution in this area. It is particularly unclear under what conditions a technological system manages to shift to a second phase, and we will therefore analyse cases in which blocking mechanisms have been overcome and a process of cumulative causation initiated, as well as cases in which system failure has occurred (Section 4).

3. Inducement and blocking mechanisms in renewable energy technology

In this section, we will illustrate the wide range and different character of mechanisms that have either induced or blocked the diffusion of renewable energy technology. We will do so by relating how these mechanisms have influenced the five functions in selected technological systems in Germany, the Netherlands and Sweden (see Figure 1). Two broad policy challenges are then formulated.

⁸Maskell (2001) provides an illustrative example of how institutions in Finland favour the wood processing industry at the expense of the wooden furniture industry.

⁹Jacobsson and Johnson (2000) and Johnson and Jacobsson (2001) elaborate on various types of ‘blocking mechanisms’. See also Unruh (2000) for an extensive review of mechanisms locking us into a carbon economy and Walker (2000) for a case study on entrapment in a large technological system.

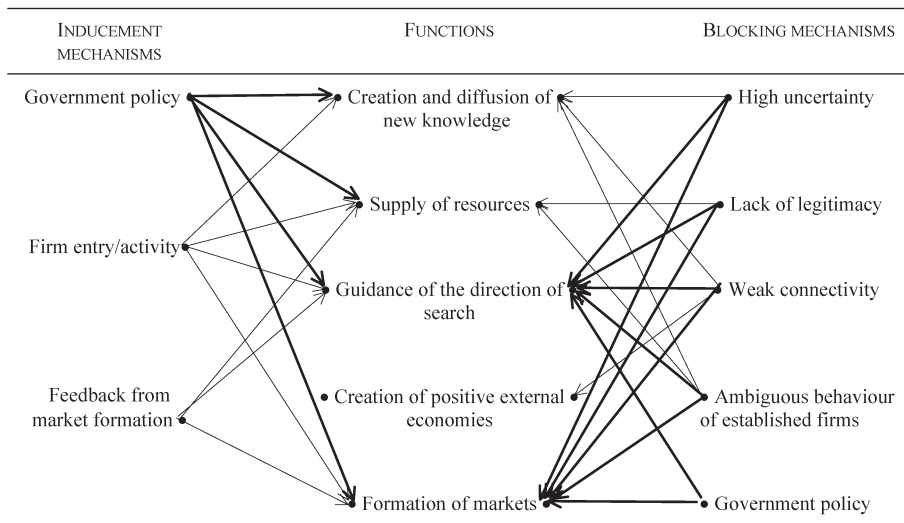


Figure 1 Inducement and blocking mechanisms for some renewable energy technologies. These mechanisms are from different cases and this table should, therefore, only be interpreted as an overview of the most important mechanisms found in the cases. Line weight illustrates the main messages of this section (see the following discussion).

Government policy has been the major inducement mechanism. R&D funding has supported the creation of new knowledge, supplied resources and guided the search of various actors to the new technologies (Johnson and Jacobsson, 2001; Bergek and Jacobsson, 2003; Jacobsson *et al.*, 2004).¹⁰ Instruments such as investment subsidies, demonstration programmes and legislative changes have stimulated the formation of markets (Johnson and Jacobsson, 2001; Bergek, 2002; Bergek and Jacobsson, 2003; Jacobsson *et al.*, 2004) and the creation of knowledge of applied nature (Jacobsson *et al.*, 2004).

Firm entry/activity has led to the creation of new knowledge, the supply of resources and the development of different types of designs within each technology field.¹¹ Moreover, it has stimulated market formation; for example, in the German solar cell case, utilities such as Bayernwerk have introduced ‘green’ pricing schemes, and the entry of firms into several steps of the value chain has led to the development of new market segments for solar cells (Jacobsson *et al.*, 2004).

Feedback loops from the formation of markets have influenced several other functions. Increased sales have generated growing resources for technology

¹⁰In the German and Dutch wind turbine cases, the funding was, moreover, used to create and sustain variety in the knowledge base (Bergek and Jacobsson, 2003).

¹¹The latter has, perhaps, been most evident in the Dutch and German wind turbine cases (Bergek and Jacobsson, 2003) and the German solar cell case (Jacobsson *et al.*, 2004), but has been seen in the Swedish solar collector and pellet burner cases as well (Johnson and Jacobsson, 2001).

development in the capital goods sector (Johnson and Jacobsson, 2001; Bergek and Jacobsson, 2003) and have also guided the direction of search of new entrants into the field of renewable energy technology, bringing with them new resources (Bergek and Jacobsson, 2003; Jacobsson *et al.*, 2004). Finally, local energy suppliers in Sweden have through their investments in bioenergy technology stimulated further market growth by increasing the legitimacy of that technology (Johnson and Jacobsson, 2001).

The first of five major blocking mechanisms is high uncertainty, in technological, economic and market terms,¹² which has obstructed market formation¹³ and guided the direction of search of potential entrants away from the field (Johnson and Jacobsson, 2001; Bergek, 2002; Bergek and Jacobsson, 2003).

The second is lack of legitimacy of the new technology in the eyes of different actors. This has not only guided the search away from the field of renewable energy technology, but has also blocked the supply of resources and the formation of markets (Johnson and Jacobsson, 2001; Bergek and Jacobsson, 2003). The most prominent example of this mechanism is the Swedish 'nuclear power trauma' (see Box 1), but the lack of legitimacy was also an important reason behind the Dutch government's failure to solve the siting problem for wind turbine, which was due to difficulties to obtain building permits (Bergek and Jacobsson, 2003).

These two blocking mechanisms are common in new technological fields and have to be handled by the emerging technological systems. However, three additional mechanisms have compounded the problem.

First, weak connectivity in terms of weak learning and political networks between actors of the technological systems has resulted in a number of problems.¹⁴ For example, problems have been wrongly formulated, have fallen between stools or have remained unsolved even though the knowledge to solve them exists in the system (Johnson and Jacobsson, 2001; Bergek, 2002). A weakness of the proponents of the new technologies in the Swedish political arena has made them unable to increase legitimacy and induce the institutional changes necessary to stimulate market formation (Johnson and Jacobsson, 2001; Bergek and Jacobsson, 2003).

Second, the ambiguous and/or opposing behaviour of some established energy suppliers and capital goods suppliers has reduced the legitimacy of renewable energy

¹²For example, it is difficult for firms to choose between different design approaches and for customers to trust that new and unproven technologies will work. Economically, the level of compensation for small-scale electricity production and the prices of other energy sources are dependent on political decisions. In the market, unarticulated demand from new customer groups makes it difficult for firms to identify markets and adapt products to customer needs.

¹³This has been true not only for large-scale process technologies such as black liquor gasification (Bergek, 2002), but also for small-scale technologies such as pellet burners and solar collectors (Johnson and Jacobsson, 2001).

¹⁴However, in some cases connectivity was too strong, which resulted in strategic conformity with respect to market and technology choices (e.g. the Dutch wind turbine case) and, thus, in increased vulnerability to uncertainty.

Box 1 The Swedish nuclear power trauma^a

The Swedish 'nuclear power trauma' has its roots in the Swedish nuclear power issue, which has been discussed since the early 1970s and which led to a referendum in 1980 after the Harrisburg accident. It was decided that the Swedish nuclear époque was to end in 2010, but the issue has still not been settled.

The energy-intensive industry, the capital goods industry and the two dominant utilities formed the core of a powerful alliance to oppose the dismantling of nuclear power. In the other camp, the anti-nuclear power movement referred to the results of the referendum and wanted to begin the dismantling process. The Social Democrats in power had considerable problems to balance the demands of the two camps, which led to uncertain and unpredictable energy policies.

Over time, a 'nuclear power trauma' emerged, which reduced all energy issues to one: the issue of whether or not to dismantle the Swedish nuclear power plants. In the very heated debate, renewable energy technology was seen only as a substitute for nuclear power, and all programmes to induce further diffusion of renewable energy technology were justified in that context.

This trauma had two major consequences for renewable energy technology. First, the value of each technology was judged in relation to how many nuclear power reactors it might replace. For small-scale technologies, it was but a fraction, at least in the short and medium term, which further weakened the legitimacy of renewable energy technology and contributed to an inability to recognize its growth potential.

Second, since renewable energy technology was perceived by many as a threat to the continued availability of nuclear power, an interest in, for example, wind power was automatically assumed to involve an anti-nuclear stance and a 'betrayal' of Swedish industry, which enjoyed the benefits of nuclear power. Thus, it was not surprising that renewable energy technology did not gain legitimacy in the eyes of the capital goods industry, potential users and large parts of the media. As a consequence, the supply of resources was constrained, the market did not grow and few firms entered the industry supplying renewable energy technology.

^aThis account is based on Jacobsson and Johnson (2000), Johnson and Jacobsson (2001) and Bergek and Jacobsson, (2003).

technology and has, thus, blocked the supply of resources and guided the direction of search away from these technologies (Johnson and Jacobsson, 2001; Bergek and Jacobsson, 2003). It has also added to customer uncertainty and vulnerability, which has blocked market formation (Johnson and Jacobsson, 2001; Bergek, 2002) and delayed important steps in the knowledge-creation process (Bergek, 2002).

Third, government policy has blocked several functions. In Sweden, a lack of conscious variety creation within R&D policy has guided the direction of search into an early selection of designs that have not been in demand, for example in the case of wind turbines. In Sweden and the Netherlands, inconsistent and changing policy measures have increased the level of uncertainty and resulted in an erratic demand for some technologies, which has guided the search of firms away from the field of renewable energy technology (Johnson and Jacobsson, 2001; Bergek and Jacobsson, 2003).

Clearly, there is a wide range of different inducement and blocking mechanisms, which influence the various functions in a multitude of ways. This implies that a first policy challenge is to create an understanding of the functional pattern of each relevant system with the purpose of identifying its particular strengths and weaknesses. A key policy objective should then be to make sure that weak functions are strengthened (by

increasing the strength of inducement mechanisms and/or reducing strength of blocking mechanisms).

In order to reduce the strength of blocking mechanisms, it is particularly important for policy to be concerned with the two functions 'guide direction of search' and 'stimulate market formation'. As is clear from Figure 1, these functions may be blocked in many ways, and there is therefore a considerable risk that their potential to influence other functions through feedback loops (as described above and in the following section) will not be realized.

Designing policies that aim at influencing the functional pattern of an entire technological system obviously requires coordination between various ministries and agencies responsible for different parts of the incumbent and emerging systems. For example, energy policy, science policy and construction norms may need to be integrated in order for a 'roof programme' promoting solar cells or solar collectors to be realized. Achieving such policy coordination is the second policy challenge.

4. The dynamics of system evolution

In this section, we will turn to the dynamics of system evolution and analyse the conditions under which blocking mechanisms in some cases have been overcome, and a process of cumulative causation started, or how the evolution of a new technological system in other cases has been stunted. In the course of the analysis, we will identify more policy challenges. We will draw upon the experiences of Germany, Netherlands and Sweden in wind turbines, Germany in solar cells and Sweden and Netherlands in solar collectors.

In Table 1, we summarize the diffusion levels at the end of a formative period (about 1990) and in 2001 in both absolute (MW) and relative terms (MW/total primary energy consumption). Three observations can be made. First, the relative German level of diffusion was between two and seven times higher than that of the Netherlands and Sweden in 2001. Second, at the end of the formative period, the Netherlands and Sweden were ahead in wind turbines and solar collectors respectively (and about equal to Germany in solar cells) but lost their advantage subsequently. Third, the Swedish advantage in solar collectors was not only lost *vis-à-vis* Germany, but the Netherlands was also catching up with Sweden.

In our attempt to explain these developments, we will begin our analysis by identifying features of the formative phase and then proceed to discuss the phase in which a market expansion begins to take place. We will argue that a necessary condition to take a lead in the transformation process is that the formative stage is characterized by certain features, but also that this is not a sufficient condition—even if a formative stage is successfully completed, the transition to a second phase is fraught with difficulties.

4.1 The formative stage

As underlined in Section 2, institutional alignment is at the heart of the process of

Table 1 The diffusion of wind turbines, solar cells and solar collectors in Germany, the Netherlands and Sweden in about 1990 and 2001 (total stock and stock related to total primary energy consumption)

	Wind turbines (MW and MW/TWh)		Solar cells (MW _p and MW _p /TWh)		Solar collectors (m ² and 1000 m ² /TWh)	
	1990	2001	1992	2001 ^a	1990	2001
Germany	68 0.016	8800 2.30	5.6 0.0014	174 0.045	282,000 0.069	3,809,000 0.994
The Netherlands	49 0.055	519 0.524	1.3 0.0014	12.8 0.013	11,000 0.013	226,000 0.228
Sweden	8 0.016	290 0.630	0.8 0.0016	2.8 0.006	105,000 0.209	217,000 0.471

Bold figures indicate the 'leading country' (of the ones presented here) at the end of the year in question.

Sources: Total primary energy consumption data for 1990, 1992 and 2000: BP (2001). Wind turbines: BWE (2002), Kamp (2000), WSH (2002) and STEM (2001, table 5). Solar cells: IEA (2002). Solar collectors: Bångens and Sinhart (2002).

^a2000 for the Netherlands and Sweden.

transformation. In the formative stage, the institutional framework has to begin to be aligned to the new technology. A third challenge for policy makers is to contribute to a process of institutional alignment (in spite of eventual attempts by vested interest groups to hinder this process). Such an alignment is multifaceted, and we will point to three types of institutional adjustment, which are required for a new system to emerge: variety in 'knowledge creation', market formation and, associated with that, gaining legitimacy for the new technology.

First, science and technology policy has to induce 'knowledge creation' in renewables. In the OECD, government R&D budgets for renewable energy technology increased substantially in the 1970s and early 1980s¹⁵ and remained broadly constant, in the order of US\$500–600m, in the 1990s (IEA, 2000). However, although the volume of funds matters, the manner in which policy is conducted is of great importance as well. As mentioned in Section 2, the formative stage is often characterized by substantial technological uncertainty and by the coexistence of many competing design

¹⁵So also did those fossil fuel and nuclear power R&D; the approximately US\$700m spent in IEA countries on renewable energy technology R&D in 1998 may be compared with the more than US\$2800m spent on conventional nuclear power R&D (excluding breeders and fusion) and US\$1400m spent on fossil fuel R&D (1999 prices and exchange rates) (IEA, 2000).

approaches. This was clearly the case for wind power in the 1980s, where designs differed greatly in terms of, for instance, size and number of blades (Bergek and Jacobsson, 2003). In solar cells, the same variety can be seen as a whole range of so-called thin film technologies challenge the dominant crystalline technology (Jacobsson, *et al.*, 2004).¹⁶ Where such technological uncertainty prevails, policy makers ought to avoid thinking in terms of optima. The guiding principle for policy should instead be to contribute to the generation of a diverse set of technological options by stimulating experimentation and the ‘creation of knowledge’ connected to different design approaches. The creation of variety is closely connected to the number of actors within a field since these may bring different types of visions, competencies and complementary assets to the industry.¹⁷ The fourth policy challenge is, thus, to induce a variety of actors to experiment with different solutions.

The German federal R&D policy consciously avoided guiding researchers and firms in any specific direction in the fields of wind turbines and solar cells. Instead, it allowed for a broad search and ‘creation of knowledge’ to take place by many different actors (e.g. firms and universities/institutes) over a long period of time (Bergek and Jacobsson, 2003; Jacobsson *et al.*, 2004). In the Dutch wind turbine case, policy and other factors induced a search in many directions as well. In the Swedish case, however, a substantial R&D funding was channelled almost solely to very large turbines (and just a few actors) as these were seen to be the only type which could have a substantial impact on power production in the medium term (see the Swedish nuclear power trauma, outlined above). In solar collectors, the early Swedish pattern was the same with an emphasis on large-scale applications, one particular design approach and a few actors (Bångens and Sinhart, 2002).¹⁸

Second, appropriate financial incentives to invest in renewables need to be put in place in order to stimulate the ‘formation of (early) markets’, with the purpose of providing ‘guidance of the direction of search’ for a variety of firms towards the new field and stimulating the ‘creation of new (application) knowledge’ and the formation of prime movers. The incentives used may, for example, be in the form of capital grants for new investments in order to absorb some of the technological and economic risks for pioneering users.

However, and third, a prerequisite for appropriate incentives to come into place, and for firms to enter the new area, is that renewables are seen as legitimate in broad

¹⁶Indeed, even in the case of the large-scale process technology of black liquor gasification, several competing technical solutions have been developed in Sweden (Bergek, 2002).

¹⁷On this point, see also van Est (1999). In addition, having a few, dominating actors in a field may be risky since such actors may very well become ‘prime blockers’ instead of ‘prime movers’. This was evident in the case of black liquor gasification in Sweden, in which the mere withdrawal of a dominant actor blocked the diffusion of the new technology (Bergek, 2002).

¹⁸Indeed, in Sweden, a bias towards large-scale solutions at the expense of variety is easily discerned, not only in wind turbines but also in solar collectors and biomass gasification technology. In all cases, this bias was later associated with a failure to industrialize the technologies.

segments of society. In Germany, the Chernobyl accident in 1986 had a permanent and major effect on the attitude towards nuclear power in the German population (Jahn, 1992) and a broad legitimacy of renewables dates back to at least 1988 when all political parties backed a Parliamentary Resolution calling for more R&D in renewables (Scheer, 2001). Incentives to invest in renewables have therefore been widely available. Wind power benefited from several federally funded demonstration programmes, which contributed to the formation of markets in the second half of the 1980s and a demonstration programme for larger solar power applications was initiated in 1986. Moreover, the German Ministry of Research responded to the above mentioned Parliamentary Resolution with a 250 MW programme for wind energy (Johnson and Jacobsson, 2001) and a highly innovative 1000-roof programme for solar cells (Jacobsson *et al.*, 2004).

The market expansion for wind turbines largely benefited German suppliers—small utilities or farmers (the first customers) often favoured local machinery firms in early user-supplier relations and indeed, much of the market created by the 250 MW programme was, by various means, ‘reserved’ for domestic firms (Bergek and Jacobsson, 2003). In total, the formative period saw the entry of fourteen German firms, which formed an industry association together with owners of wind turbines (Bergek and Jacobsson, 2003). As for wind turbines, the early market for solar cells benefited almost only German firms.

In the Netherlands, wind power had a reasonably strong legitimacy in the late 1970s and early 1980s, and some demonstration projects in the early 1980s supported new prototypes and turbines in new applications, e.g. by fiscal incentives and capital grants (Bergek and Jacobsson, 2003). In addition, investment subsidies were given to investors from 1986 due to a revived political interest in wind power after an energy price crisis in 1984. A Dutch market was formed which was larger than that in Germany in the second half of the 1980s and as many as 15–20 firms entered the wind turbine industry. As in the German case, these local wind turbine firms supplied most of the machinery.

In contrast, and as was elaborated on concerning the Swedish nuclear power trauma, a key feature of the Swedish institutional context was a failure to achieve a legitimacy for renewables that supply electricity.¹⁹ Consequently, the wind turbine market was poorly developed in the 1980s. The little market there was contained no mechanisms for favouring local suppliers with the exception of a couple of megawatt turbines. There was, however, an advanced programme for large-scale applications of solar collectors connected to district heating networks in the 1970s and 1980s, contributing substantially to the formation of an early market (Bångens and Sinhart, 2002). An early legitimacy was obtained as solar collectors were primarily seen as a substitute to oil and not to nuclear power. In this emerging market, a few Swedish suppliers were favoured (Bångens and Sinhart, 2002).

¹⁹Interestingly, after more than a decade of intense debate, the combatants were so firmly entrenched that the Chernobyl accident had little effect on public opinion on nuclear power (Anshelm, 2000).

In summary, in the German and Dutch cases of wind power, initial markets were formed, albeit small, and firms were induced to enter into the technological system. Variety was achieved through both R&D policy and from these entrants. An early legitimacy was an underlying factor. Much the same can be said about the German solar cell case (although the number of entrants into solar cell production was lower) and the Swedish case of solar collectors (although there was little technical variety). In these cases, industrial firms strengthened the technology-specific advocacy coalitions. In contrast, in the Swedish wind turbines case there was little variety, an absence of legitimacy, hardly any market formation, few entrants and, consequently, an advocacy coalition which lacked the strength of industrial firms (in spite of large government R&D expenditures in this field).

4.2 *Cumulative causation or system failure?*

A formative stage needs to be followed by one in which the initial market space is enlarged so that volume advantages can be reaped, additional firms be induced to enter throughout the value chain and further learning is stimulated. As underlined in Section 2, an enlargement of markets and the related institutional alignment involves propelling the system forward in a process of cumulative causation. In the following subsections we will unravel the characteristics of that process where it has evolved, i.e. in the German cases of wind turbines and solar cells, and discuss why it has failed to occur in other cases, such as the Dutch and Swedish wind turbine cases.

Wind and solar power in Germany: cumulative causation unravelled

The German case of wind power reveals how feedback loops may be generated from early market formation, via early entrants, to changes in the institutional framework beyond the formative phase.

Representatives of the infant wind turbine industry and independent power producers (i.e. early entrants in the form of, for instance, farmers in north-west Germany) collaborated with an association of owners of small-scale hydro electric plants (Ahmels, 1999) and with an organization of local and federal politicians favouring renewables (Eurosolar) to get the German parliament to pass its first electricity feed-in law (EFL) in 1991 (see Box 2). The broad legitimacy of renewables in Germany meant that there was little resistance to this law—indeed, the passing of it was seen as a ‘simple thing’ in terms of political effort (Scheer, 2001).²⁰

The EFL came into force in 1991. It required utilities to accept renewable electricity delivered to the grid and to pay the supplier 90% of the average consumer price (~17 pfennig/kWh) for it.

This EFL gave a massive and hitherto unheard of incentive for wind turbine owners, which resulted in an ‘unimaginable’ market growth (Bergek and Jacobsson, 2003). Due largely to this market growth, the German wind turbine industry was able to expand

²⁰With this broad legitimacy, wind and solar power have received support not only from the federal level but also from the regional and local level (e.g. in Bavaria and North Rhine-Westphalia).

Box 2 The German electricity feed-in law^a

The origin of the law was the 1989 proposal of two environmental organizations (Förderverein Solarenergie and Eurosolar) of a 'cost covering feed-in law', which was supported by an association of small-scale hydropower plant owners and the infant wind turbine industry.

Within parliament, politicians from CDU, SPD and the Greens, organized within the Eurosolar Parliament Group, worked for the acceptance of a law. With support from the majority of the CDU members (which then formed the government), the law was passed in 1991.

In the mid-1990s, the rapid diffusion of wind turbines led to a response from the larger utilities that worked vigorously to convince the German parliament that the EFL should be rescinded. Intense lobbying followed, which reintroduced substantial uncertainty, and the market stagnated. Finally, in 1997, a select committee was given the responsibility for investigating whether or not the law should be amended.

By then the German wind turbine industry had been able to grow beyond an infant stage, allowing it to add economic arguments to environmental ones in favour of wind energy. It had also formed powerful political networks that were manifested in, for example, an active industry association of turbine suppliers and owners, which through lobbying activities tried to influence the select committee.

In contrast, the utilities were supported neither by the German federation of industries (VDMA) nor by any political party.

The wind turbine lobby won the political battle, although it was a close call; in the select committee, the proponents of a continued law won the vote by eight to seven.

^aThis account is based on Johnson and Jacobsson (2001) and on Jacobsson *et al.* (2004).

rapidly in the first half of the 1990s, and yet new firms were induced to enter into different parts of the value chain (e.g. wind turbine suppliers, financiers of large wind parks and component suppliers).

These new entrants influenced the process of cumulative causation in three ways. First, they led to a strengthening of the advocacy coalition, in part because economic arguments could now be added to environmental ones in support of wind power. Indeed, the wind power coalition grew so strong that it later successfully handled challenges by the larger utilities, which wanted to change the EFL, both in the German Parliament and in the court system [especially the German constitutional court²¹ and the European Court (Jacobsson *et al.*, 2004)]. Second, the 'supply of resources' to the technological system by some new entrants allowed for a rapid upscaling of turbines as well as for building of large wind parks. Third, they allowed for a further division of labour to evolve, primarily between wind turbine suppliers and local component suppliers. The benefits spilled over to yet more turbine manufacturers (e.g. DeWind) since these could rely on a complete infrastructure, which reduced entry barriers.

Similar to the wind turbine case, early entrants and positive feedback loops associated with these strengthened the solar cell coalition in Germany as it tried to influence the institutional framework to the advantage of the new technology (see Box 3). The

²¹We are grateful to Professor Volkmar Lauber for pointing this out for us.

Box 3 The German solar cell policy process^a

In the early 1990s, the German solar cell market could not justify investments in new production plants, and by the mid-1990s there was hardly any production of solar cells in the country. The available market stimulation instruments—the EFL and the ‘1000-roof programme’—were not enough to build a larger market.

The advocates of solar power—firms and other organizations—began a struggle to stimulate market formation. In 1992, Förderverein Solarenergie proposed that more generous feed-in laws covering the full cost of electricity production from photovoltaics should be introduced for solar power by local utilities (Stadtwerke) and, together with local environmental groups and Eurosolar, managed to influence 40–45 towns to implement such laws.

Pressure built up for the federal government to follow up on the local initiatives. This pressure was augmented by an expansion of the remaining two solar cell firms in US plants and an associated threat to dismantle their activities in Germany.

In 1998, a ‘100,000 roof’ programme started, driven mainly by the Social Democrats.

In addition, the Greens wanted to move the local feed-in laws to the federal level. They organized various environmental groups, industry associations, the trade union IG Metall, three solar cell producers and politicians from some of the states that had local feed-in laws. They also received support from SPD, which had an industrial policy interest in re-writing the existing feed-in law from 1991; they feared that the liberalization of the energy market in 1998 would endanger the further development of the successful German wind turbine industry.

In 2000, the EFL was revised and the remuneration became fixed for a period of 20 years. The level varied though for the different renewables. For solar cells, it amounted to 99 pfennig for those who invested in solar cells in the first year of the law, a level which hardly would have been obtained without the very considerable interest in paying for solar electricity as revealed by the numerous local feed-in laws.

^aThis account is based on Jacobsson *et al.* (2004).

available market formation programmes (the EFL and the ‘1000-roof’ programme) were not enough to build a growing market for solar cells (the remuneration of the former was not enough to cover the high costs of solar power and the latter was not large enough). However, through a political struggle by an advocacy coalition composed primarily of environmental organizations, solar cell firms, Eurosolar and the Green party, local feed-in laws (at the municipal level) were formed and were later followed by a federal ‘100,000-roof’ programme in 1998 and a revised federal feed-in law (in 2000) with much higher remuneration than before (Jacobsson *et al.*, 2004).

An expanding market for solar cells in the second half of the 1990s greatly strengthened the function ‘guidance of the direction of search’ and new firms and other organizations entered along the whole value chain: machine suppliers and engineering firms developing production technology, solar cell manufacturers, module manufacturers, firms applying solar cells in a large number of applications (e.g. on exhibition halls, football stadiums, parking meters, etc.), tile and roof manufacturers, facade manufacturers, builders, electricians, insurance companies, city planners and, not least, architects.

This entry strengthened the process of cumulative causation in three ways. First, some of the new entrants developed the new segments of façade and roof integrated applications. The exploitation of these segments by pioneers enlarged the market and led to a strengthening of the function ‘guidance of the direction of search,’ which induced yet new entrants, contributing to the ‘supply of (more) resources’. Second, the solar cell advocacy coalition gained strength and is now raising the level of ambition by a call for a ‘10,000-façade’ programme for solar cells (Siemer, 2002). Third, new entrants helped to induce further institutional changes, e.g. in the educational system. For example, the German pioneer in solar cell facades, Flabeg, spent a great deal of efforts for about a decade to engage and teach schools of architecture so that new architects are made familiar with solar cells and acquire competence to design buildings where solar cells constitute building components.

System failures: Dutch, Swedish wind power and Swedish solar collectors

In contrast to the German wind turbine and solar cell cases, the Dutch and Swedish wind turbine and the Swedish solar collector cases can be characterized as ‘stunted’ technological systems. The Dutch wind turbine and the Swedish solar collector cases are particularly interesting as they came out very strongly from the formative period (see Table 1).

In the Dutch case of wind turbines, a ‘change in gear’ in the rate of diffusion did not occur, largely for institutional reasons: the function ‘formation of markets’ was blocked by problems in receiving building permits, and therefore did not increase greatly in strength in spite of the presence of different types of market stimulation instruments, e.g. continued investment subsidies, electricity taxation that favoured renewables and guaranteed access to the grid for wind power producers (Bergek and Jacobsson, 2003). In order to attempt to solve the building permit issue in connection with a large and potentially ground breaking investment programme, the central government made an agreement with the provincial governments as to how to distribute 1000 MW capacity of wind power. However, the agreement did not involve the local government (which issued the building permits and which had little reason to support wind power) and wind power was apparently not a sufficiently important political issue for the central authorities to impose directives on land usage on the local authorities. This may be interpreted as a failure to further develop the early reasonably strong legitimacy. With a weak local market, and with poor access to the first years of the German growth, the Dutch supplier industry began to disappear, reducing the strength of the advocacy coalition.

In the Swedish case of wind turbines, an advocacy coalition of any strength never materialized, and policies favouring wind energy were hesitant. The total size of the funds channeled to the diffusion of wind turbines in the form of capital grants were limited in both time and scale (unlike the EFL).²² Although the grants were

²²This first investment subsidy was limited to SEK 250m (approximately US\$25m) over a period of five years (NUTEK, 1993a,b).

supplemented by an environmental bonus in 1994, the incentives were much weaker than in Germany and it was not until 1996 that the utilities were obliged to buy power from independent producers at fixed price (which, moreover, was low; Averstad, 1998).²³ The most serious obstacle, however, as in the Netherlands, was problems in obtaining building permits, and the government did little to alleviate the situation. The cool attitude of policy makers, in the context of the 'nuclear power trauma' (see above) and the great strength of the advocacy coalition favouring the incumbent technologies, continued to block the transformation process.²⁴

In the Swedish case of solar collectors,²⁵ an initial advantage had been created through the exploitation of large-scale projects connected to district heating networks in the 1970s and 1980s. However, this advantage was lost in the 1990s, largely due to various mechanisms blocking the function 'formation of markets'. The bulk of the limited expansion in the 1990s occurred in the segment 'roof-mounted solar collectors for existing single-family houses'. A first blocking mechanism here was the dominance of the supplier industry by new entrants which were (i) disconnected from the networks associated with large-scale applications (that was the main receiver of government funding for R&D and connected to academia) and (ii) characterized by an underdeveloped division of labour, as well as craft-like production associated with lack of scale economies. A second blocking mechanism lay in the traditional installation industry—the industry that potential customers contact when they are to invest in new heating equipment—which did not enter the technological system since the legitimacy of solar collectors was weak in that industry and other substitutes, such as pellet burners, heat pumps and electric boilers, were advocated instead. A vicious circle emerged, where high costs; poor division of labour and weak legitimacy obstructed market formation.

Other market segments failed to develop. Particularly serious has been the near absence in Sweden²⁶ of solar collectors applied in the construction of groups of new single-family houses. The potential of this niche is demonstrated by the Dutch case (Bångens and Sinhart, 2002). In a joint programme, government, municipalities, utilities and industry targeted new residential areas and implemented measures that set in motion a process of cumulative causation. Installers and local consultancy firms were made aware of the technology through campaigns and educated in training

²³Suggestions for a feed-in law for wind turbines had, however, been made earlier—in 1986 by an expert group and in 1989 by the Centre party (a small party that has always favoured renewables).

²⁴The latest evidence of this is a Parliamentary Enquiry (see SOU, 2001), which had the task of designing a Swedish system for 'green certificates'. In the proposal, a very modest level of ambition was set for renewables, and it was explicitly stated that the expansion would take place using biomass and that any demand for additional wind turbine installations would wait until 2010 (in spite of Sweden having a large potential both on-shore and off-shore in the Baltic sea).

²⁵The case of solar collectors is based on Bångens and Sinhart (2002).

²⁶The exception is mainly a roof integrated solar collector developed by a Swedish municipal housing firm together with a building contractor, a university and a consultant firm.

programmes. The solar collectors were almost standardized, opening up for economies of scale in production. Two solar collector firms were able to grow, exploit these economies and become strong enough to form alliances with the traditional heating industry, adding legitimacy to the technology. Annual sales have now reached about 30,000 m² and most of it is in this project market.

In the Swedish case, policy makers did little to improve the legitimacy of the technology, nor to raise awareness or target new segments. Instead, the main policy issue was the high prices of solar collectors, which resulted in a series of subsidy programmes. These were, however, of small magnitude, short duration and on–off character, and caused a roller coaster phenomenon, which the industry had difficulties adapting to.

Cumulative causation and challenges for policy

In sum, a central feature of the German wind turbine and solar cell cases is the unfolding of a set of powerful positive feedback loops in the second phase, the origins of which are found in investments made in the formative period. Yet, the transition from a first to a second phase is, by no means, an easy venture. As demonstrated by the Dutch wind turbine and Swedish solar collector cases, an initially successful technological system can be stunted in its further growth. Setting in motion processes of cumulative causation is, therefore, the key policy objective, and involves the fifth and greatest challenge.

At the heart of a process of cumulative causation lies the formation of markets. A sixth policy challenge, therefore, is to implement pricing policies in the second phase which give investors benefits that are powerful (to provide strong incentives and to compensate for the inherently large uncertainties involved—see Section 3), predictable (to reduce inherent uncertainties to a manageable level) and persistent (to allow for long life times of the equipment and a long learning period). In Germany, the EFL almost fulfilled these conditions. When it was first introduced in 1991, the high remuneration was a powerful incentive for investors in wind turbines. The incentive was also reasonably predictable as it was anchored in a law, but it was not persistent as it was linked to the market price. With the revision of the law in 2000, however, the incentive was made persistent, as the law guarantees a price for 20 years to investors.

The German EFL of 1991 had another drawback (in addition to not being persistent): the remuneration was too low to stimulate a demand for technologies with a higher cost level than wind turbines, in particular solar cells. The impact of EFL on the transformation of the energy sector was, therefore, initially mainly restricted to wind turbines. Whereas it can be argued that the use of a single remuneration level is efficient (in the sense of cost-efficient), it may not be effective (in the sense of inducing a transformation of the energy sector). Clearly, a transformation of the energy sector must be built on a whole range of renewables, which will have different cost levels. Each of these need to go through an extensive learning period, but, as argued in Section 2, this will not occur if firms are not induced to enter into various points in the value

chain and firms need the incentives associated with a market to do so.²⁷ Forming markets is, thus, a necessary requirement for setting in motion a learning process.

Policy makers are therefore required to use market-forming instruments, which differentiate between renewables, although the size of the market space and the range of technologies to foster may vary between countries. Policy makers therefore need to design a regulatory framework that includes giving different prices, and price dynamics, for electricity generated by different renewables. When the EFL was revised in 2000, prices were indeed set at different levels (and with different dynamics) for different renewables (see above).

Yet, economic incentives are not enough. A large obstacle to the diffusion of wind turbines in both Holland and Sweden lay in difficulties to obtain building permits. In Germany (for the north-western states where it is windy), on the other hand, it was stipulated that if land was not designated for wind turbines, these could be set up anywhere. This had the result that wind zones were designated by local governments where it was easy to obtain permit. In the Dutch case of solar collectors, advanced building norms contributed to the expansion of solar collectors in the 1990s, as did efforts to foster a broad awareness and legitimacy for that technology (Bångens and Sinhart, 2002). Institutional alignment therefore goes beyond designing appropriate economic incentives.

5. Lessons for policy

The purpose of this paper was to contribute to the policy debate with regards to the management of the process of transforming the energy sector. In the preceding sections, we revealed central inducement and blocking mechanisms for the diffusion of renewable energy technology and analysed the dynamics of the transformation process in both successful and in less successful cases. In doing so, we identified six challenges for policy. In this section, we will first summarize these challenges and then discuss some problems for policy makers in meeting them.

The first and overall policy challenge is to create conditions for processes of cumulative causation to appear in a variety of new energy technologies. Such processes are necessary for the transformation process to eventually become self-sustained, i.e. increasingly driven by its own momentum, instead of being dependent on repeated policy interventions. What these conditions may look like and how they may be created is far from evident, however, but the remaining five policy challenges may indicate at least part of the answer.

The second challenge is to create an understanding of each technological system in order to be able to (i) specify technology specific inducement and blocking mechanisms and (ii) devise policies that influence the system's functional pattern. The latter requires, in turn, policy coordination, which is the third policy challenge. As Teubal

²⁷Implicit in this reasoning is that we do not have the time to wait until the presently lowest cost renewable has reached its saturation point before we foster other renewables.

(2001: 19) puts it, ‘the policy effort is more complex than what would seem to be the case in a Neoclassical world; and . . . policy coordination . . . is an important . . . aspect of such an effort’.²⁸

The fourth challenge is to begin to contribute to a process of institutional alignment in the formative stage in the evolution of a technological system and the fifth is to induce a variety of actors to experiment with different design approaches.

The sixth and final challenge is related to the transition from the formative stage to a stage characterized by rapid and sustained diffusion of the new technologies. It involves the implementation of powerful, predictable and persistent pricing policies in order to create favourable conditions for investors in renewable energy technology. Policy makers also need to make sure that these pricing policies are technology specific so that learning may occur in different technologies simultaneously.

These policy challenges are useful in that they formulate the relevant policy problems. However, the difficulties involved in solving them should not be underestimated. We will point to three issues that policy makers will need to deal with in meeting these challenges. The first refers to the inherent difficulties in predicting the outcome of policy intervention in complicated and complex systems. The second issue is the time scale involved, reaching over decades. The final issue is the political nature of the process of aligning institutions and new technology.

First, policy makers need to achieve an understanding of the complicated and complex structure and dynamics of each technological system. It is complicated in that it is empirically difficult to identify, trace and assess the strength of various mechanisms, which induce or block the diffusion process. Even ‘simple’ relations, such as what blocks the formation of markets, may be obscure. It could be due to a lack of legitimacy, siting problems (for wind turbines), relative prices or a combination of several of these factors (see section 3). It may therefore be difficult to understand what to do to stimulate, for example, market formation²⁹—several factors may need to be influenced simultaneously and the outcome of any intervention is uncertain.

The complexity of the system is due to the prevalence of feedback loops. Such ‘causal inter-relations within the system itself as it moves under the influence of outside pushes and pulls and the momentum of its own internal processes’ (Myrdal, 1957: 18) are very difficult to predict, which implies that the properties of a new system emerge in ways that are difficult to foresee. For example, in the late 1980s, nobody could have foreseen

²⁸In contrast to what is perceived in the traditional ‘linear’ view of innovation, the functions of a technological system have to be served simultaneously. This implies that science, technology and market stimulation policies have to be run in parallel, not in sequence. This may apply not only to a formative period but beyond it where policy may need to combine efforts to expand the space for the new technologies with efforts to maintain diversity (Jacobsson *et al.*, 2004).

²⁹This was evident in the case of black liquor gasification, in which policy was limited to R&D grants and investment subsidies in spite of the fact that lack of knowledge and economic uncertainty were not the greatest obstacles to commercialization of the technology (Bergek, 2002).

the formidable success of the German wind turbine industry or the failure of the Dutch only a few years later (see Box 4).

Of course, feedback loops make the results of any intervention additionally uncertain. For instance, what effects may a particular market stimulation programme have on firm entry, and what effects will the pattern of entry have on network formation and strength of advocacy coalitions? The German case of EFL (see Box 2) illustrates this uncertainty by revealing how interventions to support one technology had unforeseen effects on other technologies. The owners of small hydroelectric plants initiated the law and gained support in parliament, but the main beneficiaries were the wind turbine owners and the wind turbine industry. Furthermore, the expansion of wind power subsequently helped to pave the way for a revision of the EFL, which provided an opportunity for the solar cell advocacy coalition to (successfully) argue for an inclusion of solar cells in the revised law (see above). The outcome of policy is thus difficult to predict.

Second, the time scale involved is very long. In Germany, signs of a self-reinforcing process could not be seen until about the mid-1990s, i.e. after about two decades of activities. After entering into diffusion processes with self-reinforcing features, additional time is required for the emergence of complete technological systems with the capacity to significantly impact on the energy system (see Appendix Table A2). Abatement policies, aiming to substantially reduce the emissions of CO₂, must

Box 4 German and Dutch wind turbine industry developments in the 1980s^a

In the 1980s, both Germany and the Netherlands developed a set of industrial firms, with experience in building a few hundred turbines. In Germany, about 15 firms entered in the mid-1980s, and 11 firms still existed in 1989. In the Netherlands, 15–20 firms entered in the late 1970s and early 1980s. In the late 1980s, many firms left the industry, and in 1989 the industry was dominated by only five firms.

On the market side, the German market remained weak throughout this phase; the total installed power was less than 20 MW by the end of 1989. In the Netherlands, an investment subsidy was introduced in 1986, which resulted in a small market expansion. By the end of 1989, the total installed power was 33 MW.

Around 1989, both Germany and the Netherlands designed market formation programmes of similar sizes. In Germany, the federal 100 MW programme aimed at installing 100 MW of wind power. The Dutch electricity suppliers initiated the Windplan project, aiming at installing 50 MW per year over a five-year period. Both these projects were huge in comparison to the then current stock and market size.

At this point in time, the Dutch industry must have seemed as likely to succeed as the German (if not more). The Windplan project was much larger than the German 100 MW programme, and over 90% of the first 75 MW were reserved for Dutch firms.

However, whereas the 100 MW programme successfully induced virtuous circles of market growth, increased industry resources and growing political strength, Windplan ended abruptly (in part due to the siting problem) and most Dutch firms failed. Had instead the Dutch been successful with their programme (as many Dutch and foreign firms expected them to be) and the German programme failed (something which was entirely conceivable), the Dutch today could be the ones catching up with the leading Danish industry.

^aThis account is based on Johnson and Jacobsson (2001).

therefore include policies that aim at fostering the formation of new technological systems. Building these new systems requires patience—in order to allow for cumulative causation to appear—and flexibility—in order to be able to adapt to conditions that are bound to change but without unduly increasing uncertainty.³⁰

Third, the political struggle over the institutional framework may be intense. Thus, policy makers need to find a strategy whereby they can eventually challenge and overcome opposition from incumbent actors in order to align the institutional framework to the new technologies. Part of this strategy needs to deal with how to foil attempts by incumbent vested interests to capture the state and hinder an institutional alignment simply by having more resources at their disposal than the representatives of infant industries and underdeveloped markets.

Whilst these institutional changes are vital, their scope is limited in a formative period. Since the scale of activities is low, incumbents may not see the new technology as dangerous and may, therefore, choose not to obstruct the formation of the infant technological system. In Germany, resistance from utilities emerged only after wind turbines had begun to diffuse rapidly in the first half of the 1990s. This resistance was met by an increasingly powerful advocacy coalition in favour of wind energy, drawing strength from a combination of broad legitimacy for renewables and their growing economic importance. Although it was not an explicit strategy, the German policy used small steps to build an embryonic technological system before the incumbents were challenged.

In contrast, in the Swedish case, renewables were put forward as substitutes to nuclear power, not only by environmental groups but also by two political parties, which advocated a closure of newly built nuclear plants. The subsequent referendum on nuclear power held in 1980 (see above) had the clear effect of heightening the awareness of the coalition favouring nuclear power to a perceived threat of renewables, long before these had developed into realistic substitutes. Henceforth, there was fierce resistance to any policy measure that could benefit renewables, and had the 'small thing' of the German EFL been passed in Sweden, it could well have led to the downfall of the government.

Dealing with these three issues requires policy makers to develop a range of characteristics—high analytical competence, in-depth knowledge of relevant technological systems, coordination skills, patience, flexibility and political strength—characteristics which policy makers can neither automatically be assumed to have, nor be expected to develop.

Policy makers may, however, gain access to at least some of these characteristics by working with members of different technology specific advocacy coalitions, both private capital and various interest organizations. Industrial firms clearly strengthen these coalitions in terms of knowledge, power and other characteristics. This refers in particular to capital goods firms but also to firms 'downstream'. The expansion of the

³⁰Kemp *et al.* (1998) underline the role of learning and adjustment in their approach of 'transition management'.

actor base of the technological system—its enlargement—is therefore a vital element in the evolution of the technological system, not only in terms of learning, but also in terms of developing these characteristics within the technological system. Indeed, several German organizations worked with industry representatives as well as with local and federal politicians to strengthen the function ‘formation of markets’ by forming coalitions of system builders, and thus proved to be critical for the evolution of the technological systems centred on wind turbines and solar cells.

Policy makers may therefore find it useful to strengthen existing advocacy coalitions by creating favourable conditions for private capital, in particular in the capital goods industry, and to support the work of various interest groups associated with the new technology. Perhaps the main ‘output’ of the formative stage lies in a technology-specific advocacy coalition that can support elements of the state in overcoming various blocking mechanisms. This is a strategic role of the national supplier industry. It is strategic not only in that it can help to educate local customers (Carlsson and Jacobsson, 1991), but also in that it strengthens the advocacy coalitions. With a supplier industry, the ‘green’ is ‘industrialized’.

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Table A1 Diffusion of some 'new' renewable energy technologies

	Stock (gross) ^a (2001)	Average annual growth (%) in stock ^b (1990–2001)	Energy supply ^c (2001)
Wind power (world)	25.7 GW ^f	27	56 TWh ^g
Solar cells (world)	1.7 GW _p ^h	22	2 TWh ^e
Solar collectors (Europe) ^d	11.1 million m ²ⁱ	12	6 TWh ^j

^aInstalled wind power capacity; solar cell shipments/production; solar collector area.

^b'Growth in stock' is an elaboration on 'Stock' and is based on the same sources.

^cWind turbine electricity supply; solar cell electricity supply; solar collector heat supply.

^dSolar collector diffusion data have not been available on a global level.

^eAssuming that 1 W_p is roughly 1.33 kWh electricity supply.

Sources: ^fBTM (2000, table 2-1), DWTMA (2001), European Commission (1997, table 2-2), Kåberger (1997) and *Windpower Monthly* (2002); ^gelaboration on *Windpower Monthly* (2002) and EWEA *et al.* (1999); ^hCurry (1999), *Photon International* (2002), *PV News* (1993, 1997) and Ruber and Wettling (2001) (minimum values); ⁱEkvall *et al.* (1997) and DFS (2002); ^jelaboration on DFS (2002), Stryi-Hipp (2000) and Soltherm (2002).

Table A2 Estimated share of the increase in world electricity use of wind and solar power (TWh)

	2000	2010	2020
Wind power supply increase	8.2	100	368
Total supply	37	445	2967
Solar cell electricity supply increase	0.3	3.8	72
Total supply	1.7	17.8	280
Total increase wind and solar	8.5	103	440
Electricity use increase	462	628	729
Total use	15,381	20,873	27,351
Share of increase in electricity use (%)	1.8	17	61

This table is based on assumptions and data provided by EWEA *et al.* (1999) (wind turbines) and Greenpeace and EPIA (2001) (solar cells). The increase in electricity supply is assumed to be 3.1% per annum until 2010 and then 2.74 % per annum until 2020. The market for wind turbines (annual installed MW) is assumed to increase with 20 % per year until 2003, 30 % until 2010, 20% until 2015 and 10 % until 2019. The market for solar cells is assumed to increase by roughly 27% per annum 2000–2010 and by roughly 34% per annum 2010–2020.

Sources: Elaboration on EWEA *et al.* (1999) and Greenpeace and EPIA (2001).