Analyzing emerging innovation systems: A functions approach to foresight

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Abstract: The success of sustainable innovations depends in a large part on their environment, the innovation system. Insight into the structure and dynamics of the innovation system is thus of crucial importance in foresight studies and policy analysis. The analytical framework outlined in this paper allows us to study the relations between the components, the structure and the functionality of the innovation system resulting in increased insight in (future) system behaviour and performance. Furthermore, mapping the (actor-independent) functions of the innovation system allows us to compare different cases, enabling timely and adequate policy measures through improved foresight. The application of our framework to the California wind energy innovation system shows a relation between system structure and performance and gives us insight in system dynamics.

Keywords: foresight, innovation systems, innovation policy, functions of innovation systems, wind energy

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1 Introduction

Innovation is a key determinant for long term economic growth and development. But the innovation process is characterized by uncertainties, high risks, huge investments and late returns on investment which make it a complex process. This is particularly true for sustainable innovation where market forces alone cannot be relied upon to realize the desired transitions. To overcome existing system inertia, governments try to manage sustainable technology development (Weaver et. al., 2000) through environmental and innovation policy programs that lean on foresight programs (Martin and Johnston, 1999, Miles, 2005, Blind et.al, 1999). Insight into the structure and dynamics of emerging technologies through normative foresight can help policy makers to influence the direction of the innovation onto a socially desirable path (Linstone, 1969). As noted by Archibugi and Lundvall (2001) this is a very difficult task since “most innovation policies are well suited when it comes to supporting existing technological systems, but much less when it comes to stimulating the creation of new ones.” There thus exists a need for effective information on such emerging technologies (Coates et. al., 2001).

In this paper, we present a functions of innovation systems framework that allows us to study the relations between the components, the structure and the functionality of (emerging) innovation systems resulting in increased insight in (future) system behaviour and performance. We apply our framework to the California Wind Energy Innovation System (CAWEIS), a well documented and researched example of sustainable development, see for example Norberg-Bohm (2000) and van Est (1996). Renewable energy technologies, like wind energy, are technologies that radically change the embedded technological system. Innovation is needed to introduce new energy technologies, to rearrange the infrastructure, to adjust traditional working methods and to solve many problems along the way. Complex system, such as the CAWEIS are characterized by uncertainty in technological developments (Nelson and Winter, 1977, Wilson, 2004), bounded rationality of actors (Simon, 1957), feedback processes (Lundvall, 1988, Rosenberg and Kline, 1986) and path dependencies (Arthur, 1994). Furthermore, external factors such as global politics, fossil fuel prices and electricity imports also influence the CAWEIS, and make foresight exercises extremely difficult.

Influencing technological change towards a sustainable direction does not only involve technical change but also changes in the social dimension, such as user practices, regulation, and industrial networks (Geels, 2002, Linstone, 2004). The concept of "Innovation System (IS)" is a heuristic attempt developed to analyse all such 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, Sagar and Holdren, 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 IS 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 IS. An IS 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 IS is “The network of institutions in the public and private sectors whose activities and interactions initiate, import, modify and diffuse new technologies”. Applying the systemic aspect of the systems of innovation approach to understanding technological change has large implications. The systemic character of technological change explains why technological change is often a very slow process and why it is so difficult to influence (Smits and Kuhlmann, 2004). After all, the rate and direction of technological change is not so much decided through a simple competition between different technologies, but is predominantly decided through competition between various existing innovation systems, both fully developed and emerging ones.

The primary goal of the CAWEIS is the diffusion and use of wind energy, this makes the CAWEIS a technology specific innovation system:

> Network(s) of agents interacting in a specific technology area under a particular institutional infrastructure to generate, diffuse and utilize technology. Technological systems are defined in terms of knowledge or competence flows rather than flows of ordinary goods and services. They consist of dynamic knowledge and competence networks (Carlsson and Stankiewicz, 1991).

This means that all organizations, institutions and relations involved in the diffusion and use of wind turbines are included in the wind innovation system, this includes influences of different sectoral and national systems. This decision is in line with previous studies by Hekkert et. al. *(forthcoming)* and Orozco (2004). A technology specific IS can be described by three main components: *actors*, *institutions* and *networks*. These three components are interrelated and have a common goal, which in our case is the successful diffusion of wind energy technology.

In a technology specific IS the number of actors, networks and relevant institutions is generally much smaller than in a national system of innovation, a commonly used level of aggregation. This reduces the complexity and therefore, on this aggregation level, a dynamic analysis seems well possible. Jacobsson and Johnson (2000) even state that the technology specific approach is the most dynamic of all the IS approaches.

However, while there currently is a strong emphasis on comparing the structure of different systems and thereby explaining the differences in performance, less emphasis is placed on the analysis of the dynamics of innovation systems. A technological system is not static but evolves with alterations in the content of technologies and products as well as in the relationships among the various technologies (Carlsson et. al., 2002). In other words, if we are to analyze a technological system we need to understand the dynamics that make the system change and evolve over time.

In this paper we claim that the analysis of technological change should focus on systematically mapping the *activities* that take place in innovation systems that result in technological change. Since these activities have the function to contribute to the goal of the innovation system, which is the generation and diffusion of innovations, the activities are often called *functions of innovation systems* (Jacobsson and Bergek, 2004).
Jacobsson and Johnson (2001), Liu and White (2000) and Rickne (2000) have defined basic functions that need to be served in a technological system. The (future) performance of an innovation system can then be measured (or predicted) by analysing how these functions are facilitated by the system. Miles (2005) also describes foresight as contributing to the functioning of innovation systems. Furthermore, this close relation between, foresight, system performance and policy is in line with the recommendation of Georghiou (*forthcoming*) who states that foresight and system behaviour should not be treated as separate processes.

The central aim of this paper is to empirically validate the concept of functions of innovation systems and demonstrate how this framework contributes to better foresight and policy recommendations. Furthermore, the proposed theoretical framework makes it possible to compare different innovation systems and explore the relation between innovation system structure and performance.

The paper proceeds by giving an outline of our theoretical framework in section 2, followed by the analysis and discussion of the CAWEIS in section 3. Finally, general conclusions are presented in section 4.

2 Theoretical framework: components, structure and functions

This section describes the boundaries and components of the CAWEIS, the system under investigation. We analyze the Californian wind energy innovation system over a time span of 30 years, starting with the first oil crisis in 1973. Within this 30 year time frame, we define 5 distinct periods determined by key events that had a profound effect on the CAWEIS and the fulfilment of the functions. For each of the periods we will analyze CAWEIS components, structure and functionality as well as the relations between these system characteristics.

2. 1 CAWEIS components and structure

We include all organizations, institutions and relations involved in the diffusion and use of wind turbines as well as external influences such as fossil fuel prices in our analysis of the CAWEIS. We follow Kleinschmidt (2004) in depicting innovation system components and structure (see Figure 1).

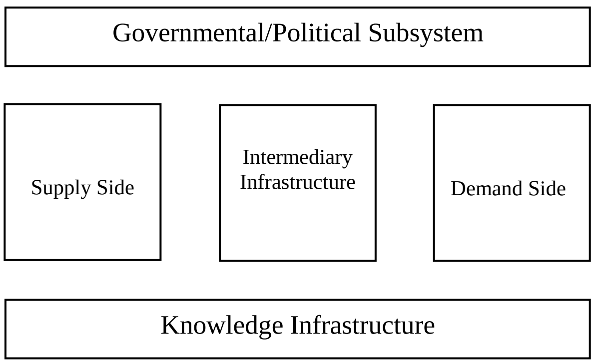

Figure 1: Components and structure of the innovation system.

The *supply side* covers the actors that are involved in the physical production process of wind turbines. This includes (a) large established manufacturers, such as General Electric and Boeing, (b) new technology-based companies, which enter the wind turbine market, (c) suppliers of wind turbine components, such as generator manufacturers, and (d) specialized suppliers such as turbine blade manufacturers. The *demand side* consists of actors that consume wind energy directly, such as wind farmers and utilities, or indirectly such as households or industries that use wind generated electricity.

The *intermediary infrastructure* comprises institutions and organizations aiming at improving the interface and knowledge flow between the supply and demand side, such as project developers. The *knowledge infrastructure* encompasses all organizations that support the other subsystems by generating, assessing and transferring knowledge. Examples of organizations within this subsystem are public research institutes, private R&D facilities as well as organizations within the educational system. Finally, the *governmental subsystem* consists of government agencies, such as the California Energy Commission (CEC), the Department of Water Resources (DWR), the U.S. Department of Energy (DOE) and the California Public Utilities Commission (CPUC).

The particular CAWEIS structure in each period is determined by how well developed each of the components is and by the relations that exist between components. A subsystem is well developed when it contains a diversity of actors, which are actively contributing to the diffusion and use of wind turbines.

2.2 Functions of innovation systems

We analyse the relation between CAWEIS structure and performance (over time) through the functions of innovation systems concept. This allows us to measure performance of (emerging) innovation systems by mapping how well each function of the IS is fulfilled. Applying the functions framework will help us to gain insight in the relation between structure and performance as well as the dynamics of the system. Thereby aiding policy makers in their assessment of the (desirability of the) direction of the CAWEIS as well as provide guidelines for additional policy measures. Below, we will give a short description of each of the seven functions.

F1. 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, see i.e, 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.

This function can be analyzed by mapping the number of new entrants, the number of diversification activities of incumbent actors and the number of experiments with the new technology.

F2. 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, (2004), 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).

Three typical indicators to map this function over time are: 1) R&D projects, 2) patents, and 3) investments in R&D. While these indicators map the effort put into knowledge development, one might also map the increase in technological performance by means of so called learning curves (Frenken et. al., 2004).

F3. Knowledge diffusion through networks

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.

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. An example of learning by interacting through networks is the process of venturing, in which a firm can acquire new capabilities and competencies in cooperation with another firm. Rickne (2001) argues that networking often leads to new resources for innovation such as: intellectual capital, financial capital and physical capital, thereby stimulating the market and diffusion of a certain technology. 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 from public research to productive sector. Few firms have the resources to take the risks of developing a new technology (industry), of which objectives are uncertain, when it has no clear estimate of payback (Autio and Hameri, 1995).

This function can be analysed by mapping the number of workshops, conferences and research collaborations devoted to a specific technology topic and by mapping the network size and intensity over time.

F4. Guidance of the search

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 function can be analysed by mapping specific targets set by governments or industries regarding the use of a specific technology and by mapping the number of articles in professional journals that raise expectations about new technological developments. By counting the number of articles that are positive or negative regarding the new technology development, the state of the debate can be assessed. Foresight or forecasting exercises also provide guidance for the system (Georgiou, *forthcoming*).

F5. 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'. Because of this it is important to create protected spaces for new technologies. Furthermore, 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.

This function can be analysed by mapping the number of niche markets that have been introduced, specific tax regimes for new technologies, and new (environmental) standards that improve the chances for new environmental technologies.

F6. 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 (2002) and Johnson (2001) emphasize competence and capital as the most important resources for innovation. An important group of actors in creating resources to tackle a problem or to explore technological opportunities is the venture capital industry. A proposal for a venture should identify potential opportunities for positive synergies across existing technologies, in terms of technology, market and management capacity.

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.

F7. Creation of legitimacy/counteract resistance to change

In order to develop well, a new technology has to become part of an incumbent regime, or has to even overthrow it. The economic potential of a new technology is not a direct indicator for the capacity that will be realized in practice. The decisive factor is the motivation of investors to invest in this technology, and the acceptance and utilization of wind energy by the operator as well as the public. (Jahraus et al, 1991). 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)*, favourable 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.

This function describes activities that influence the acceptance with respect to policy, industry and, society of the technology on different levels of the system and can be analysed by mapping the rise and growth of interest groups and their lobby actions.

2.3 Methodology: measuring system performance

Measuring the performance of a technological system is not straightforward but requires careful consideration of the level of analysis applied and the degree of maturity of the technological system (Carlsson et al 2002). Many studies focus on diffusion of new technological knowledge as an indicator for system performance since diffusion curves are easy to construct and diffusion is the final stage of development and application of new knowledge (Hekkert, 2004). However, this may not be such a good performance indicator for emerging systems where the diffusion has yet to take off. Furthermore, when emerging systems do show a high diffusion rate this is not necessarily a sign of a mature and well functioning innovation system. Such 'premature take-off' was observed in the CAWEIS and will be described in more detail in the next section. The functions of innovation systems approach allows us to use other indicators for the performance of the developing CAWEIS. The use of several indicators is in line with recommendations by Carlsson et. al., (2002) who state that several indicators rather than a single one are preferable, in particular when it comes to assessing the performance of emerging technological systems.

In this study we use the functions and their related indicators to assess CAWEIS performance. Data about the CAWEIS was gathered through event analysis Van der Ven et. al., (1999). Furthermore, interviews with important actors from all system components were conducted to get a complete overview and to include different perspectives in our analysis. The analysis of key events is presented in the next section, for a full event record we refer to Kleinschmidt (2004).

3 The California wind energy innovation system (CAWEIS)

California has been involved with the development of wind energy from an early stage. A favourable political and financial climate resulted in a chain of wind energy developments, which gave California a frontrunner position in the wind energy market until the late 1980s. After that point in time California lost its position to countries such as Denmark and Germany. The initial hype around wind in California is clearly illustrated by Figure 2 and Figure 3, which show diffusion (measured by installed capacity) and federal funding of R&D respectively. If we consider the learning curve for wind energy in Figure 4, we notice that the wind energy hype occurred at a time when the technology was still immature and not competitive with respect to the incumbent technology. However, we do not observe an increase in the rate of diffusion when the technology does reach this competitive stage, indicating that other factors besides knowledge development are important. The stagnating diffusion can be explained by factors ranging from an immature state of the technology to environmental opposition and low gas prices, illustrating the need for a systems approach to the analysis of the CAWEIS.

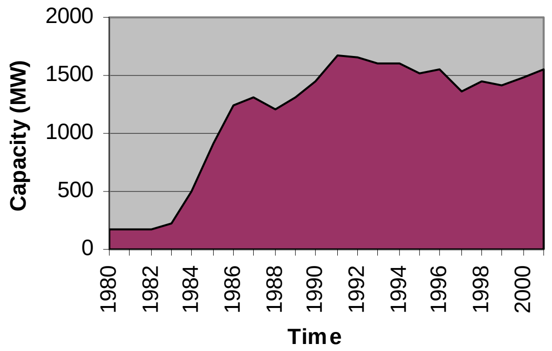

Figure 2: Total installed capacity in California. (CEC, WPRS reports 1980 – 2001)

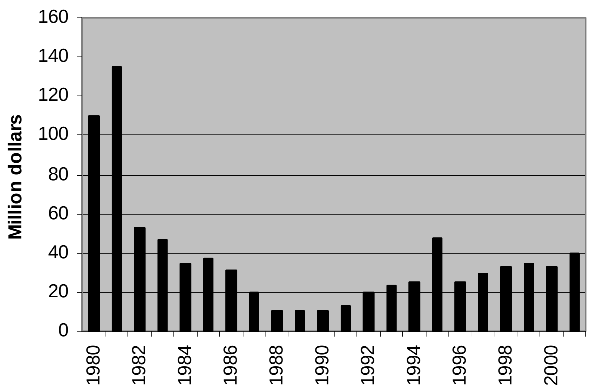

Figure 3: Federal funding of wind energy R&D. (GAO: 1980 -1996 and AWEA, 1997 -2001[1])

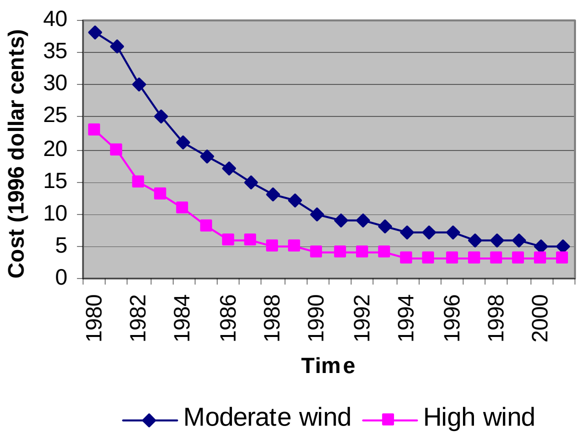

Figure 4: Learning curves for wind energy (GAO, 1999)

[1] Fiscal year 1978-92 figures represent actual spending. Fiscal year 1993-98 figures represent adjusted or actual appropriations.

Period 1 (1973-1978) Changing priorities

The first oil crisis led to revised energy policy both at federal and state level and is one of the main events leading to the emergence of the CAWEIS. Figure 5 shows the incomplete CAWEIS structure of this first period. The emphasis of the innovation system was on government, supply side and knowledge infrastructure.

The governmental and political subsystem initiated most activities in this period, however federal and California state government had different visions on wind energy. The DOE allocated resources for innovation to public research laboratories (knowledge infrastructure) and large established manufacturers Boeing, Westinghouse Electric Company, Hamilton Standard and General Electric Company (supply side) to develop and construct large prototype wind turbines in the context of the Federal Wind Energy Program (FWEP). FWEP stimulated wind energy through mission-oriented supply side incentives and focused on large-scale wind energy development (van Est, 1996, Lerner and Ginosar, 1979).

Contrary to this focus on large scale, in California the small-scale distributed energy paradigm was stimulated through the Soft Energy Policies of the Brown administration. The emphasis with regard to sustainable energy technology had therefore been on solar energy. However, The FWEP also raised awareness about the potential of wind energy in California. Towards the end of the period an assessment of the California Energy Commission (CEC) showed that California possessed some excellent wind sites. This led to a change in the renewable energy focus of California and Solar Tax Credits also became available for wind energy. Furthermore, the administration facilitated wind energy development with supportive legislation and initiatives. However the IOUs fiercely defended their monopoly position and opposed this trend by imposing very strict conditions and regulations for the use of wind energy. Below we will describe how these events contributed to the functionality of the CAWEIS.

Functional pattern period 1.

F1: Some *entrepreneurial activities* were performed in the context of the FWEP program where the DOE allocated resources for innovation to public research laboratories and large established manufacturers (Boeing, Westinghouse Electric Company, Hamilton Standard and General Electric Company) to develop and construct large prototype wind turbines. However no entrepreneurial activity was found at the demand side or the intermediary subsystem.

F2: The FWEP also stimulated research driven *knowledge development*: The national renewable energy laboratory (NREL) and the National Aeronautics and Space Agency (NASA) facilitated this function by conducting fundamental research in wind energy, see Arthur (1982) and Norberg-Bohm (2000). The manufacturers created knowledge through learning by doing during the construction and evaluation of the prototypes.

F3: The cooperation between the large manufacturers, DOE, NASA and NREL created *knowledge diffusion* through learning by interacting. This cooperation thus created a research based innovation network between public research laboratories and the turbine manufacturers.

F4: The emphasis of the activities in the emerging CAWEIS was on *guidance*. The awareness about the need for more sustainable energy technologies resulting from the first oil crises was a major factor in the emergence of the CAWEIS.

The FWEP raised expectations and created awareness of the potential of wind energy. The federal government and the California State Government both guided the direction of the search but with different priorities. On federal level there had been chosen for energy technologies that fitted the traditional paradigm of large-scale central energy production.

In California, on the other hand, the Soft Energy Policies of the Brown Administration guided the direction of the search towards small-scale distributed energy generation. The Brown administration believed solar energy would have the most potential to fit this paradigm. As a result wind energy had a low priority in the beginning of this period. There thus existed a misalignment between the guidance at the federal and at the state level.

In the last phase of the period, the Brown administration became more wind energy minded and started to change the institutional setup in favour of wind energy. Tax credits, previously only available to solar energy, became also available for wind energy and the administration facilitated wind energy development with supportive legislation and initiatives. The Californian Energy Commission (CEC) carried out an assessment which showed that California possessed some excellent wind sites.

F5: The function *market formation (f5)* was insufficiently addressed during this period due to a lack of demand side initiatives. The federal government only supported the mission oriented R&D innovation strategy, and overlooked the market-oriented insights of actors within production and consumption of wind energy (van Est, 1996). This impeded user-producer relations between potential large-scale wind turbine manufacturers and electric utilities, leaving the wind energy business without a market. Moreover, the incumbent utilities obstructed small-scale wind energy development by using their established monopoly position as the sole provider of electric services. “The distribution of small wind turbines was blocked by all kinds of rules imposed by the utilities. This raised the price for extra equipment so much that it was not worth buying a small wind turbine for private use (Don Smith, 2004).

F6: Government agencies such as the Department of Energy (DOE), the Office of Appropriate Technology (OAT) and the California Public Utilities Commission (CPUC) allocated financial *resources* for innovation to public research laboratories and large established manufacturers in the context of the FWEP. The companies themselves also invested capital, competences and technological resources

F7: The function *creation of legitimacy* was insufficiently addressed in this period. This is illustrated by the fact that many wind energy initiatives in California were impeded by the unsupportive regulatory system (van Est 1996) as well as by the successful opposition from the IOUs.

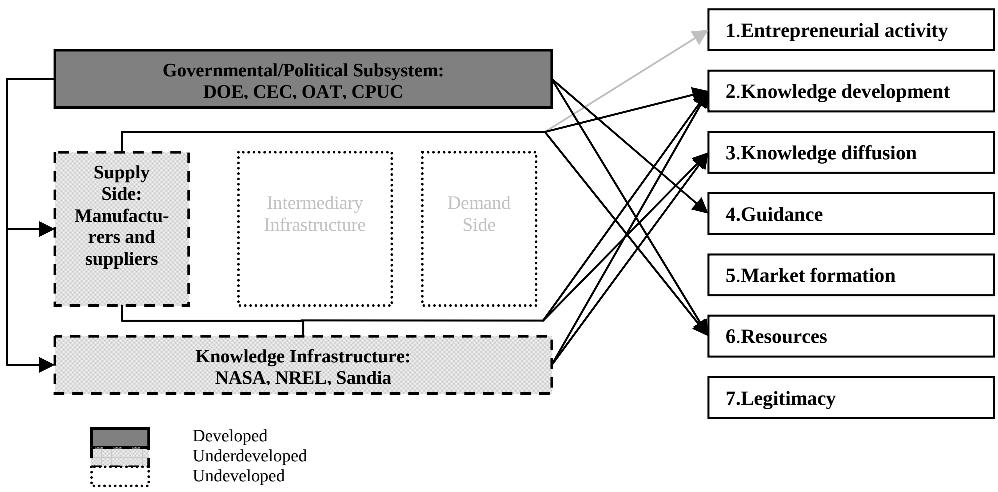

Figure 5: Structure, relations and functionality of the CAWEIS in the period 1973-1978.

Summarizing we can see that not all functions were adequately addressed during this first period of development of the CAWEIS. Furthermore, the functions were addressed by a limited number of actors only. The CAWEIS is thus incomplete with respect to both structure and functionality in this period. This is an indicator that the system is not ready for successful large-scale diffusion.

Period 2 (1978-1986): The Californian wind boom

This second period is characterized by a large rapid diffusion of wind turbines. When we look at the system structure of this period (Figure 6) we can see that the CAWEIS shows a progressive development. Not only did the subsystems develop through new entrants that became heavily involved with wind energy, but additionally there were relations established between the supply side, the intermediary infrastructure and the demand side subsystem.

The passing of the Public Utility Regulatory Policies Act (PURPA) in 1978 allowed third-party power producers, which ended the monopoly power of the IOUs (Asmus, 2001). California created an extremely favourable climate for third-party power producers by implementing this law with additional State tax credits and the highest buy-back rates of the U.S. The newly created niche market attracted the attention of entrepreneurial companies and pioneers, which became involved in wind energy development (Gipe, 1995). The entrepreneurial companies consisted of turbine manufacturers, wind farmers, and wind project developers. Furthermore the entrepreneurs unified in lobby groups, such as the Independent Energy Producers (IEP) association and successfully influenced the regulatory system.

However, there was a lack of activities at the supply side of the CAWEIS. Federal stimulation was concentrated on the commercialization of wind energy in which demand side incentives were given priority over supply side incentives, such as R&D. President Reagan decreased the FWEP R&D budget in 1983 (see Figure 3). In California, Proposition 13 limited the budgets for governmental programs and expenses. The cuts in R&D budgets severely damaged the knowledge base of wind energy, which resulted in wind turbines of poor quality. Policy makers mistakenly estimated that the technical knowledge available for making wind turbines was sufficient. Towards the end of the period Danish manufacturers entered the Californian turbine market and were able to meet demand, thereby sustaining the fast diffusion and saving the CAWEIS. Below we will describe how these events contributed to the functionality of the CAWEIS.

Functional pattern period 2.

F1: The newly created niche market attracted the attention of entrepreneurial companies and pioneers, which became involved in wind energy development. The entrepreneurial companies consisted of turbine manufacturers, wind farmers, and wind project developers.

F2: The lack of supply side incentives and supportive legislation to improve turbine performance and quality resulted in an underdeveloped technological knowledge base. NREL and NASA were involved in turbine testing, but there was a serious lack of testing facilities, quality/performance standards and simulation software. The heavy competition in the CAWEIS resulted in radical new turbine designs without the incremental process that is needed to improve performance (Karnøe, 1995). However manufacturers did not manage to create a production line for a specific turbine design, which limited possible cost reductions.

Knowledge development activities in this period were limited to learning processes (learning by doing and learning by using) that occurred during production and maintenance of wind turbines. “The manufacture companies did their own maintenance and learned a great deal from their installed turbines” (S. Larwood, 2004).

F3: The fierce competition and secretive attitude in the wind industry prohibited learning by interacting, thereby limiting the possibilities for *knowledge diffusion*.

F4: Guidance was also not strongly facilitated in this period. Although the financial and institutional support created acceptance in the first phase of this period, the lack of performance standards or priorities in governmental stimulation of wind energy development allowed gaming (abusing) of the tax credits and the production of bad performing wind turbines. This had as a result that resistance against wind turbine installation was increasing towards the end of the period.

F5: The passing of PURPA in 1978 facilitated *market formation* by allowing a third party power producer and providing energy tax credits, thereby creating a niche market for wind energy.

F6: The competency and capital of the companies that entered the wind energy business gave wind energy development more *resources* for innovation. The entrepreneurial companies were also active in creating a capital market for wind energy. The availability of investment capital attracted even more companies to the wind energy business.

The ISO4 contracts also provided more resources for innovation making wind energy economically more attractive resulting in an expanding market. However, overall resources for wind energy R&D decreased substantially in this period due to budget cuts at both the federal and the State level.

F7: Entrepreneurial lobby groups like the Independent Energy Producers Association (IEP) started to articulate the voice of the wind industry thereby contributing to the *creation of legitimacy.* The IEP association used its political power to influence the Power Purchase Agreement (PPA) negotiations with utilities. The actions of CEC and CPUC clearly show that the institutional setup including the regulatory system changed in favour of renewable production. One major example is the ISO4 long term contract but CEC’s penalty against PG&E for failure to make reasonable efforts to promote renewables and CPUC’s embracement of renewables are also examples of the changing institutional setup.

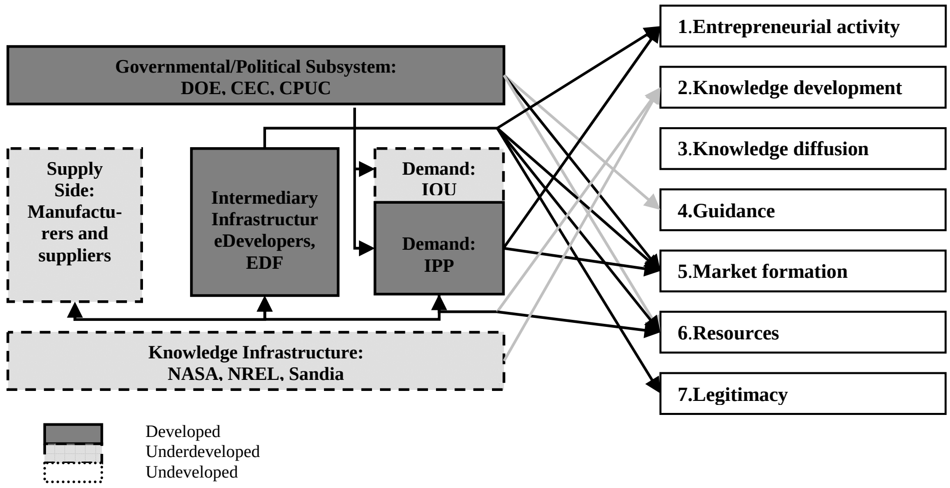

Figure 6: Structure, relations and functionality of the CAWEIS in the period 1978-1986.

To summarize, the institutional setup and financial incentives in this period were favourable enough to create a niche market for wind energy in California. However, important parts of the CAWEIS were underdeveloped (supply side, knowledge infrastructure) and not all functions were adequately addressed. This indicates that the commercialization of wind energy began too early and was not supported by the CAWEIS. The wind energy industry did not manage to achieve enough learning to produce a cost-competitive wind turbine for commercial use. The governmental cuts in R&D budgets caused a broadening of the gap between the market and the available technological expertise.

Period 3 (1986-1996): After the wind boom

This period starts with the years after the wind boom, where a weakening demand, an underdeveloped technological knowledge base and a bad image of the sector (tax scandals) caused companies and investors to terminate their involvement in wind energy development. When the demand side incentives expired, the return on investments reduced severely which reduced the capital flow into the wind energy business. The bubble of high expectations began to collapse and the immaturity of the wind industry became visible. This resulted in a smaller system and a weaker system structure with undeveloped subsystems that facilitated few functions.

In the second phase of this period, political and industrial momentum for wind power expansion was building up again, which resulted in the system structure and functionality depicted in Figure 7. The wind turbine manufacturer, US Windpower (USW), shifted its focus from the production of small-scale wind turbines to the production of medium-scale wind turbines for utility use, which opened up negotiations with the utilities. USW and the utilities aligned their competing interests which resulted in a feasibility study, followed by the establishment of a consortium between USW, the utility funded Electric Power Research Institute (EPRI) and the utilities. The consortium's goal was to produce a cost-competitive commercial wind turbine. These cooperative research activities resulted in innovations (variable speed technology) and cost reductions. In contrast with the former periods research resulted in more applicable knowledge and was conducted in conjunction with both the demand (utilities) and supply (manufacturers) side of the wind energy innovation system.

DOE responded to these activities by launching a new federal wind energy program. Funds were made available to support the cooperation between NREL, and two large manufacturers to develop and produce the advanced wind turbine. An important characteristic of this period is that wind energy development was strongly driven by an industrial initiative instead of government incentive schemes alone.

The enactment of the Energy Policy Act in 1992 reintroduced a tax credit system, that aimed at the production of electricity instead of turbine capacity, thereby stimulating turbine manufacturers to focus on the performance of wind turbines (Guey-Lee, 2001, IEA, 2001). The Energy Policy Act also changed the institutional set-up by allowing all private entities a small-scale energy production installation (Norberg-Bohm, 2000). However, few private power producers invested in wind energy, because gas turbines and cogeneration were far more competitive than wind energy as a result of low gas prices during the 1990's. The strong rise of the cogeneration industry resulted in a break up of the unified independent power alliance, which weakened the wind lobby.

But the intermediary organization Center for Energy Efficiency and Renewable Technology (CEERT), was effectively lobbying for the renewable energy business. This resulted in the renewable set-aside law which demanded that a specific portion of future electrical generating capacity would be reserved for renewable energy sources (Est, 1996).

Other important events in this phase were the standardization and certification activities and the formation of several wind energy platforms such as the Utility Wind Interest Group (UWIG), the National Wind Coordinating Committee (NWCC) and the Utility Wind Turbine Performance Verification Program (GAO, 1996, Ancona and Goldman, 1996). However, in the third phase of this period the ending of the ISO4 contracts, the starting restructuring debate and the low gas prices made an end to the fragile cooperation between utilities and the wind industry. Below, we will describe how these events contributed to the functionality of the CAWEIS.

Functional pattern period 3.

F1: *Entrepreneurial activities* were mainly initiated by USW's desire to (cooperatively) build a medium scale cost-competitive wind turbine.

F2,F3: The consortium between USW, ERPI and the utilities facilitated *knowledge development* through learning by interacting as well as knowledge diffusion. Furthermore, the production tax credits resulting from the Energy Policy Act also stimulated wind turbine performance improvements.

F4: First, the formation of the consortium gave the wind energy business a new impulse, which raised expectations and built up momentum. The new federal wind energy program that was launched by the DOE in response to these activities provided additional positive *guidance* for the CAWEIS.

Second, standardization and certification activities forced the wind industry to make performance improvements, thereby reducing the risk of wind energy investments. Another important *guidance* event was the enactment of the Energy Policy Act (EPA) which constituted a priority shift from investment to production tax credits.

However, the CAWEIS also experienced *negative guidance* during this period. CEC's attempt to provide the wind industry with a substitute for the ending ISO4 contracts failed when the Final Standards Offers number 4 (FSO4) contracts were declared illegal by FERC. The wind industry then had to negotiate Power Purchase Agreements with the utilities, but the utilities preferred more cost competitive alternatives such as cogeneration. The strong competition from the cogeneration industry in the 1990's thus provided negative guidance for the CAWEIS. The willingness of the utilities to participate in wind energy diminished even further with the start of the restructuring debate about the liberalization of the energy sector.

F5: The production tax credits created a *market* for wind energy. The created demand for wind turbines was smaller than during the wind boom, but no longer biased by extremely favourable incentives. The Energy Policy Act also changed the institutional setup by allowing all private entities a small-scale production installation.

F6: Through EPRI the utilities provided USW with additional *resources* in terms of funds and competencies. However, the ending of the ISO4 contracts, combined with low gas prices made the price for wind energy fall from 12 to 3 dollar cent per kilowatt hour.

F7: Several lobby groups emerged during this period such as the Utility Wind Interest Group and the National Wind Coordinating Committee. The Utility Wind Turbine Performance Program was especially designed to resolve barriers experienced by utilities.

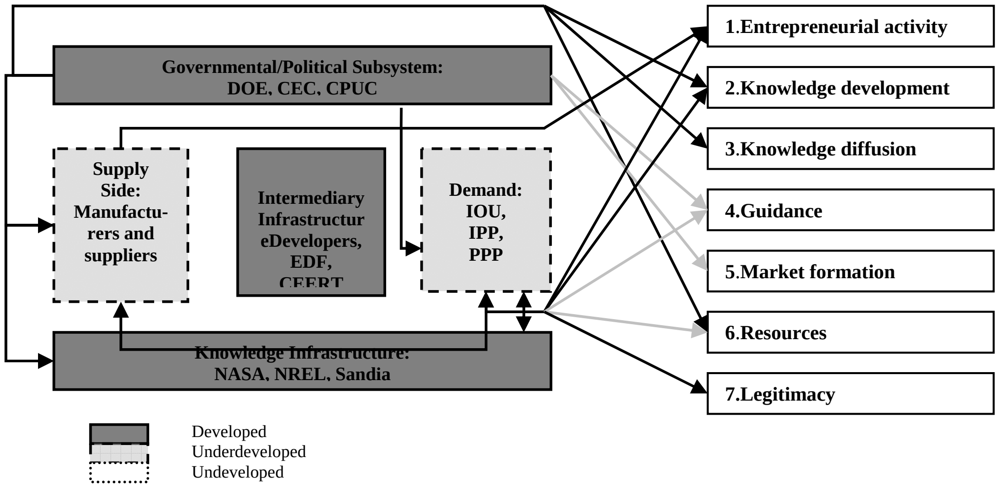

Figure 7: Structure, relations and functionality of the CAWEIS in the period 1986-1996.

Summarizing, we see that although the wind industry did not manage to create a process of mass production, it did achieve major cost reductions and produced a commercial medium scale wind turbine. However, competition from the gas industry, the ending of the ISO4 contracts and uncertainty resulting from the restructuring debate left the wind industry in a difficult position. We thus see that actors from all subsystems are active in the CAWEIS but that not all functions are adequately fulfilled. Specifically the lack of guidance resulting from both financial and regulatory uncertainty makes it difficult for actors to determine their best strategy.

Period 4 (1996-2000): Towards a restructured market

This period is characterized by the restructuring of the electricity market into a free market and the energy crisis that took hold of California in 2000/2001.

In 1996, California enacted Assembly Bill 1890, a final step towards the liberalization of the electricity market which influenced all subsystems in this period. The deregulation caused underdeveloped supply, demand and intermediary subsystems, few interactions between the subsystems and the facilitation of fewer functions (see Figure 8).

The liberalization of the electricity market increased competition, stimulated short-term management and created uncertain market conditions which resulted in a poor financial climate and a radical reduction of demand (Beck et. al., 2002). The bankruptcy of prime movers Kenetech Windpower and FloWind caused a loss of competence for the wind energy industry (GAO, 1996).

The newly created competitive free market did not only block investments in new wind energy capacity or R&D, but also jeopardized the established generation capacity. And although the governmental subsystem was less dominant in the restructured CAWEIS, it adopted the Public Goods Charge (PGC) system, established an Independent System Operator (ISO) and created direct access for green electricity producers (IPP) in order to reduce these negative effects on the wind energy business, see Moore (2000). The California Government also provided resources for new renewable generating capacity through the CEC Renewable Energy Program. However, the IPPs did not manage to negotiate Power Purchase Agreements (PPA) with the utilities, and the rewarded capacity could not be installed (CEC, 2002), resulting in 1300MW of rewarded wind projects waiting for a PPA to receive the funds.

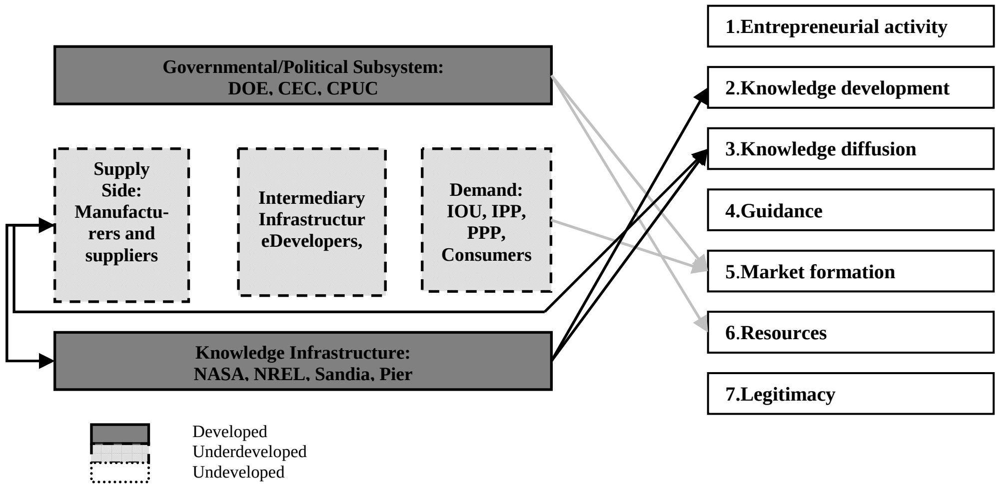

Figure 8: Structure, relations and functionality of the CAWEIS in the period 1996-2000.

Although there were still federal wind energy programs such as the Next Generation Wind Turbine Project and the Wind Powering America program, national energy policy gave hardly any priority to renewables. Furthermore, uncertainties about many issues such as the extension of tax credits did not stimulate investors

The period ended with the Californian energy crisis of 2000/2001. To avoid bankruptcy of the Californian IOUs, the governor decided to cancel the Power Exchange and suspend direct access, which resulted in the end of a growing green electricity market. One positive side-effect of the energy crisis, however, was a renewed interest in emerging renewables (CEC, 2002,2003). Below we will describe how these events contributed to the functionality of the CAWEIS.

Functional pattern period 4.

F1: In 1996 Kenetech filed for bankruptcy protection and in 1997 another domestic manufacturer, Flowind, filed for bankruptcy protection too (GAO, 1996). Zond Energy Systems remained the only domestic manufacturer that could produce large capacity machines.

F2, F3: A 1996 DOE study showed that private industry was shifting its R&D priorities away from the longer term benefits of basic and applied research to an emphasis on process enhancement on the short term (GAO, 1996), this had a negative impact on the *knowledge development* function of the CAWEIS. The establishment and funding of the Public Interest Energy Research (PIER) group within the Renewable Energy Program resulted in cooperative R&D activities with innovative turbine companies in order to reduce the cost of wind turbines. Furthermore, the federal government stimulated wind energy through federal wind energy programs. In 1997 DOE launched the Next Generation Wind Turbine Project and in 1999 Wind Powering America was launched. This Program created *knowledge* about low-speed wind energy.

F4: There were hardly any priorities given to renewables in the National Energy Policy presented in 2001, resulting in a passive investment climate where investors were waiting on the PTCs to come back. Moreover, the focus of the federal wind energy policy was shifting away from California to other states with excellent wind regimes, like Texas. This could also be seen in the targets of the wind powering America program which focused on exploiting areas with good wind resources outside California.

The period ended with the Californian energy crisis of 2000/2001. The energy crisis affected renewable energy not only indirect through the financial crisis of the utilities but also in a direct way when the governor decided to suspend direct access. A positive side effect of the energy crisis is that interest in emerging renewables increased dramatically due to concerns about black outs and increasing electricity rates (CEC, 2002). "In the general population renewables got new acceptance and interest from the energy crisis. But at the utility/merchant generator level, the crisis mentality promoted putting up natural gas plants as rapidly as possible at any price." (D. Smith, 2004).

F5: AB1890 contributed negatively to *market formation* for the CAWEIS since the CAWEIS lost its protective market and could not supply electricity at spot market prices without financial incentives. The Californian Government tried to support the struggling wind energy business. AB 1890 also created direct access which allowed IPP's to bypass the Power Exchange and sell their electricity directly to green electric service providers. This facilitated market creation and a small green electricity market emerged. "Even though direct access offered IPP's a new market, it did not create real financial benefits for the IPP's. The problem was that most of the premiums paid for green electricity were appropriated to green electric service providers instead of the wind energy." (N. Rader, 2004).

CEC's Renewable Energy program was instrumental in supporting the supply and demand of renewables within the market based system of AB1890. The auctions articulated a demand for wind turbines and created a potential market. However the IPPs did not manage to negotiate power purchase contracts and the rewarded renewable capacity could not be installed. This resulted in 1300MW of rewarded wind projects waiting for a PPA to receive CEC's financial resources for innovation. The PPA negotiations presented a barrier that severely limited the *market creation* effect of the auctions.

F6: CEC also supplied *resources* for innovation to innovative wind turbine companies with a focus on cost reduction through the Public interest Energy Research (PIER) group. With the enactment of AB1890 California also adopted the Public Goods Charge System. The PCG was effective in keeping existing renewable energy online when the financial climate for wind energy became real bad but was not powerful enough to create more demand. Until this policy was adopted the installed capacity was declining but when the PCG funds filled up the price gaps between the market gap and the actual costs for wind energy, the market stabilized again (N. Rader, 2004).

F7: Utilities feared that fluctuations in energy supply, caused by an intermittent energy source, would jeopardize the reliability of the grid. The establishment of the Californian Independent System Operator reduced this barrier by ensuring the grid's reliability.

Summarizing, we see that the institutional change needed to restructure the electricity market created blocking mechanisms that prohibited the fulfilment of the functions market creation and resources for innovation. Short term management, competition, uncertainties about the market conditions, the absence of a capital market and institutional barriers are examples of such blocking mechanisms that limited the facilitation of the functions in this period. The Californian energy crisis further limited the fulfilment of the functions market formation and resources mobilization but created positive guidance for renewable energy technologies.

Period 5 (2001-2003): After the energy crisis

The energy crisis caused the government to change its regime from a free market model to a regulating authority model, resulting in a CAWEIS structure similar to that of period 4 (see Figure 9).

The IOUs were on the verge of bankruptcy and unable to buy electricity from IPPs or to invest in new generating capacity which created shortages in electricity supply and unstable electricity prices. To overcome this situation the Californian Government ordered the Department of Water Resources (DWR) to be the only buyer of electricity and to negotiate new PPAs for additional generation capacity. To restore stability of the electricity prices as soon as possible the DWR focused on gas-fired peak performance facilities resulting in a lack demand for wind generated electricity (Clark, 2001, Asmus, 2002). The establishment of the California Power Authority (CPA) did not change this situation (Bolinger and Wiser, 2002). Although it signed letters of intent for 1800 MW of new wind energy capacity, it could not proceed because the state was not creditworthy enough.

In 2002 the California Government created the Renewable Portfolio Standard (RPS) which requires retail sellers of electricity to increase their sales of electricity, produced by renewable energy sources by at least 1 percent per year, achieving 20 percent in 2017 at the latest (CEC, 2003). The RPS promotes competition among renewable energy developers and technologies to meet the standard at the lowest cost (Herzog et. al., 2001). "However, the effectiveness of the RPS will depend on the negotiations for standard contract terms, grid integration issues and transmission issues. Only a few contract terms have been standardized, so far, which is partially the result of a divided wind power lobby (N. Rader, 2004)."

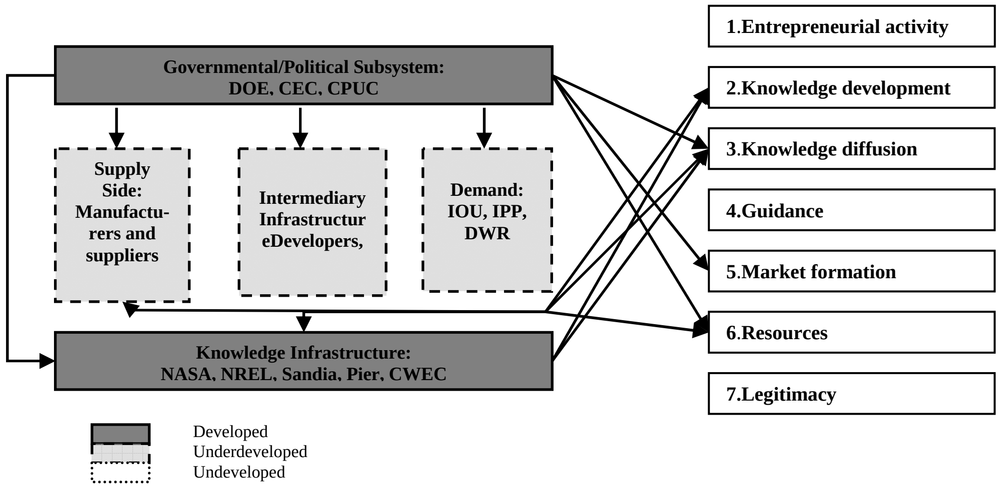

Figure 9: Structure, relations and functionality of the CAWEIS in the period 2001-2003.

In spite of the political support for wind energy and the efforts of the CEC to stimulate a wind energy market, wind turbine installation is still very low in California. Different factors hinder the adoption of wind energy. Community resistance, avian issues and environmental impact studies have created a strong opposition, which is delaying permit acquiring for wind energy projects. Furthermore the inflow of potential new wind turbine manufacturers on the Californian wind energy market is limited by a GE patent on variable speed technology (the dominant technology). Finally the Californian wind energy business still suffers from uncertainty due to inconclusive national energy policies (CEC, 2003).

Functional pattern period 5.

F2, F3: The California Wind Energy Collaborative (CWEC) is a cooperative research initiative between the University of Davis, the wind industry and CEC to deal with grid integration issues (Nakafuji, Smith, 2003) and thereby contributing to *knowledge development and diffusion*. Furthermore, the NREL and turbine or component manufacturers are cooperating in turbine testing and certification.

F4: Federal renewable energy policies remained unclear on many issues, which resulted in year-to-year budgeting on wind energy policy. This lack of *guidance* is reflected in the uncertain provision of the PTCs and the absence of the PTCs in 2004. There is a strong correlation between the availability of PTCs and wind energy investments. This created boom and bust periods in wind energy development and is keeping the wind energy business dependent on inconsequent energy policies. “A lot if companies are waiting to invest in wind energy until the PTC comes back. It would almost be better to have no credits at all, than the boom and bust periods we are experiencing now” (J. Mcnerny, 2004). Furthermore there is a strong environmental lobby against windpower.

F5,F6: The renewable portfolio standard can play an instrumental role in re-establishing a *market* for wind energy in California.

At this moment the Californian wind energy innovation system seems on the verge of a new diffusion period. The implementation of the Renewable Portfolio Standard (RPS) can induce a new period of rising cumulative capacity. In other case studies a positive relation between RPS and wind power development is found (Menz and Vachon, 2006). California still possesses excellent wind sites and has the potential for 6000MW of wind capacity. The price of wind generated electricity has come close to point where it can compete with fossil generated electricity and the prospective of rising prices of fossil fuels in the near future will make wind energy even more competitive. Furthermore, the knowledge infrastructure and the supply side of the system incorporate enough knowledge and competencies to support a strong diffusion period.

However, these drivers will have to challenge some strong blocking mechanisms which are still present in the Californian wind energy innovation system. First of all, the integration of an intermittent energy source and the construction of transmission lines to remote areas for wind energy exploitation represent important barriers. Overcoming these barriers requires adequate fulfilment of the functions, *knowledge development and diffusion and creation of legitimacy*. Future negotiations between wind energy project developers and utilities will determine to what degree the integration and transmission costs will be internalized in the price of wind energy and thereby also determine how competitive wind energy will be. Furthermore there are still the standard contracts terms that need to be negotiated between utilities and project developers and outcome of these negotiations will to a large degree determine the market conditions (market formation), strong guidance is necessary to ensure alignment of all CAWEIS subsystems. It is therefore important that California government will streamline these negotiation processes to avoid unnecessary delays. Fulfilling those conditions is a prerequisite for the establishment of the CAWEIS as an attractive environment for entrepreneurial activity.

4 General conclusions

Emerging innovation systems are characterized by complexity and path dependency. The analysis of the CAWEIS has demonstrated that structural analysis and traditional indicators alone do not provide sufficient insight in the dynamics of such systems. The functions of innovation systems framework in this paper enables normative foresight studies that guide the emerging innovation system towards a more sustainable future. This framework uncovers the feedback relation between system structure and performance and leads to conclusions on the structural, the functional and the policy level.

	Period 1	**Period 2**	**Period 3**	**Period 4**	**Period 5**
F1: *Entrepreneurial activity*					
F2: *Knowledge development*					
F3: *Knowledge diffusion*					
F4: *Guidance*					
F5: *Market formation*					
F6: *Resources*					
F7: *Creation of legitimacy*					

Table 1: Fulfilment of the functions of the CAWEIS where darker shades indicate a more adequate fulfilment.

Table 1 gives an overview of the functionality of the CAWEIS in the different periods. Here we see that different functions were dominating each of the periods. Furthermore we see that periods with large diffusion are characterized by more complete functional patterns than periods of inactivity in the CAWEIS.

	Period 1	**Period 2**	**Period 3**	**Period 4**	**Period 5**
Governmental/Political subsystem					
Supply side					
Intermediary infrastructure					
Demand side					
Knowledge Infrastructure					

Table 2: Structure of the CAWEIS where darker shades indicate a more developed subsystem.

On the level of system functionality, we see that facilitation of the functions and evolution of the system structure follow a similar pattern but that a well developed structure alone does not necessarily indicate large-scale diffusion (see for example period 3). Our case study provides reasons to believe that this correlation between functionality and systems structure is mutual. When the structural components become more developed and the interaction between the structural components increases, the system functionality also seems to improve. Thus we conclude that apart from addressing all the functions of the CAWEIS it is also important that system components are well development and that there is alignment of the components in order to achieve successful diffusion of wind power.
We notice that the way in which the functions *entrepreneurial activity* and *market creation* are fulfilled strongly influences system behaviour. This is consistent with findings in other case studies, e.g., (Hekkert et al, 2006). These functions appear to be key activities that stimulate the fulfilment of the other functions.

Furthermore, *knowledge development* also was crucial throughout the evolution of the system, ranging from mostly fundamental and technical knowledge in early development phases mostly fundamental and experimental knowledge is created to applicable, problem solving knowledge for cost reduction and performance improvement when the technological system enters the market. The fact that the knowledge infrastructure hardly created any applicable knowledge during the wind boom created a barrier for wind energy development.

On a structural level, our most important observation is that structural development alone is a necessary but not a sufficient condition for performance. The relations between structural components however, do provide insight in (future) system behaviour. The interface between the supply and demand side of the system also is an important indicator for system functionality. This is illustrated by the observation that it was often the interaction between system components rather than a single component that contributed to function fulfilment. Whenever there was an imbalance between the supply and demand side or when the interaction between these subsystems became blocked, system functionality declined and wind energy development collapsed.

Finally, with regard to policy we find that short-term policy and short-term management practices are blocking mechanisms for new technological systems such as the CAWEIS, because new technologies are often not competitive on the short run and need a long-term vision to develop.

Furthermore, system failures that occur in former periods still influence current performance. In our case premature convergence toward a particular design, namely large-scale wind turbines, decreased system variety and led to incompetent technology. Third, radical institutional changes are harmful to the emerging technological system, because their system structure is only weakly developed and can easily disintegrate. In our case study the liberalization of the electricity market and the energy crisis of 2000/2001 almost destroyed the wind energy innovation system, affecting both system structure and functionality.

The analytical framework outlined in this paper allows us to study the relations between the components, the structure and the functionality of the innovation system resulting in increased insight in (future) system behaviour and performance. The application of our framework to the California wind energy innovation system shows a relation between system structure and functionality. This systems approach allows us to gain insight in performance and system dynamics that cannot be explained by more traditional performance indicators such as diffusion rates alone. With respect to foresight the functions of innovation systems approach provides insight on two levels. First, functional analysis of the system in one period gives us insight in the behaviour of the system in the period under investigation as well as in future periods. Second, this structured approach makes it possible to systematically compare empirical data about different emerging technologies which will help us recognize the patterns of success and failure, providing increased foresight and allowing timely interventions

Implications of this research towards energy policy indicate that policymakers should formulate energy policies on system level and not on specific actors or groups of actors alone. Furthermore, policymakers should formulate long-term and consistent policies in the case of emerging energy technologies.

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