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# Generating Innovation Scenarios using the Cross-Impact Methodology

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**Abstract**

The question why and how innovation occurs is a subject of hot debate in policy, science, and economy. We describe a judgmental approach to innovation systems research that accounts for the complexity and interdisciplinary character of innovation processes and policy impacts. An interdisciplinary expert panel developed a qualitative model of an innovation system for a set of five energy technologies. The model's systemic implications are analyzed using cross-impact techniques. The findings offer reasons why technology characteristics influence innovation and diffusion prospects, why different technologies require different innovation policy measures, and why innovativeness is more robust for some technologies than for others.

*Keywords: innovation; innovation system; energy technology; cross-impact analysis; qualitative model*

JEL: O10, O30, Q40

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## 1. Introduction

Innovation has become a hotly debated topic in both political and science circles over the last decade or two. Both advanced and developing economies are attempting to improve their competitive advantages through a stronger focus on innovation. The evidence, however, challenges the commonplace belief that putting more money into basic science will, at the end, deliver innovations that the market will absorb. The market mechanism alone will not automatically lead to more innovativeness. Social scientists in many disciplines have worked on developing a more fine-grained understanding of innovation processes. However, the solutions they offer are typically not straightforward and generalizeable to all settings. Research has shown that the success factors for innovations are sector and technology specific, and that nations differ in their propensity to innovate. Based on the finding that institutions vary in their impact depending on the type of innovation and the time it takes for innovations to succeed, a common argument is that innovation policy should adjust the institutional framework so that it meets the specific requirements of the technological system in question (cf. Jacobsson et al., 2002: 3). The key difficulty here concerns the ability to predict which innovations will finally succeed in the marketplace.

This obviously complicates the development of recommendations for improving the innovativeness of a specific entity such as a firm or a cluster of firms. To be able to select specific, well-adapted styles of management and consistent strategies for institutional intervention, science management, and funding arrangements, one needs to understand the different patterns of knowledge production, the distinct styles of knowing and learning, and different forms of knowledge governance (Rammert, 2006: 258). Industrial innovation is a process that is distributed in multiple spaces, including firms' internal and external places of knowledge production, user-firms, producer-firms, small start-up firms, well-established large corporations, and heterogeneous institutions like science, economy, and government. Innovation is pushed and pulled by a highly diverse spectrum of actors that includes university departments, governmental research institutes, and risk capitalists. The boundaries between scientific innovations have been blurring, especially in high-technology and new economy sectors (Rammert, 2007: 265). It is, therefore, appropriate to develop policy recommendations that combine the expertise of a variety of individuals and organizations in the technology and institutional system. This reflects one of the key lessons learned in recent innovation studies, namely that the pooling of knowledge from different arenas is a precondition for successful innovation in a knowledge economy (so-called cross-fertilizations).

With these considerations in mind, we assembled for the present study a research team at the University of Stuttgart to explore the usefulness of a novel approach: the use of a cross-impact methodology for studying critical success factors in the innovation process. Based on the premise that success factors are specific to sectors and technologies, the project concentrated on several distinct energy technologies. The research described in this paper was part of the Mex V project of the Forum for Energy Models and Energy-Economic Systems Analysis (FEES), funded by the German Federal Ministry of Economics and Labor. FEES is a communication platform for German energy modelers and analysts used to exchange scientific knowledge and practical experience. The Modeling Experiment V - Innovation and modern energy technology (Mex V) of the forum started in 2004 and was completed in 2005. Fourteen research institutes participated in this project, examining various quantitative techniques to modeling innovation (FEES, 2005, 2007). In contrast to the mainly quantitative orientation of the project at large, the research group we assembled at the University of Stuttgart used a qualitative modeling approach. This approach was regarded by the FEES steering committee as useful for exploring the embeddedness of innovation processes in polity and society, while the mathematical approaches were considered more appropriate for modeling innovation driven changes of technological quantities such as the efficiency and costs of a particular energy technology.

In the following section of this paper, we outline the general nature of the innovation processes which will be the foundation for our analysis. In section 3, we describe select energy technologies as well as their context. Sections 4 and 5 provide a brief overview of cross-impact balance analysis (CIB) and the procedures we used to solicit expert input. Section 6 outlines the qualitative systems model of the innovation system we investigated. In section 7, we describe the results of the model analysis. We conclude with some comments about the emergent, multilevel nature of innovation processes, and the importance of public policies in these processes.

## 2. Innovation Processes envisaged in Modern Theory

The starting point of recent discussions about innovation in Germany and many other European countries has been the impression that their economies are innovation laggards in the "globalizing" world economy when compared to the innovation performance of the United States and other leading industrial economies. The result has been to stimulate concern in business and policy circles for the conditions that may be expected to generate innovation and to translate innovation into economic growth and employment creation.

A key concern has been the observation that markets often do not absorb new promising technological developments to the extent expected. This is true particularly in the field of energy technology and supply, a sector which is characterized by extremely long investment cycles. Energy systems throughout Europe are being privatized and deregulated, thus shifting control from a single decision maker to an open market that includes many actors. This new environment includes many decision makers who have different objectives, often based on a different logic and grounded in different assumptions. In line with the aims of market liberalization, several policy instruments have been put in place, with different objectives ranging from enforcing compliance with $CO_2$-abatement targets and safeguarding regional employment levels to defining specific industry policy targets. Some of these instruments, such as the German feed-in scheme for electricity produced from renewable energy sources, have successfully triggered a dynamic innovation process in specific technologies (e.g., wind, photovoltaics). Others, such as the support scheme for combined heat and power generation, have failed to provide the expected incentive for innovation (e.g., fuel cells). In the European context as a whole, instruments such as quotas or auctions with tradable certificates have often produced disappointing results. Ongoing efforts to achieve European harmonization of instruments that support renewable energy sources and combined heat and power generation make it highly desirable to achieve a better understanding of the likely effects of these instruments on innovation.

The years since the 1980s have produced a steady stream of research on innovation.[1] Studies have improved our understanding of the role played by innovation for long term

[1] For a review of research conducted from different disciplinary perspectives, see Blättel-Mink (2006), Fagerberg et al. (2005), Braun-Thürmann (2005), Hauschildt (2004), Lang and Sauer (1999), Freemen and Soete (1997) and Hanusch/Pyka (2007).

economic growth and development as well as and social change. However, we know much less about the processes and mechanisms of innovation and about the effectiveness of policy tools intended to support innovations. Innovation research has so far concentrated either on a systemic analysis of innovation processes or on in-depth studies of individual innovations. While firms (and other organizations) are usually treated as key actors in the innovation process, it has also been generally recognized that firms do not innovate in isolation. Innovating firms are interdependent; they depend heavily on interaction with actors in their various environments and have to be characterized as a collective process fed by many different sources (Lazonick, 2005; Hauschildt, 2004). Several concepts have been introduced in this literature, most of which imply that "systems" and "networks" are involved in innovation and the diffusion of innovations in economy and society.

The notion of systems of innovation, defined locally, regionally, sectorally, or nationally, has been widely used to map and explain the interactions between the actors that generate and use new technologies. "Innovation Systems" can be defined as the cluster of agents and their competencies, institutions, policies, and practices that determine an industry's or nation's capacity to generate and apply innovations. The focus on innovation systems stems from a tradition begun by scholars like Nelson (1993) who introduced the concept of "National System of Innovation", and supported by a series of industry studies (Mowery and Nelson, 1999). The Innovation Systems approach has generally adopted the principles of evolutionary economics to explain the development of technological innovations as cost efficient and marketable solutions to problems, focusing on the techno-economic opportunities (Carlsson, Stankiewicz, 1991). From this perspective, successful innovations not necessarily are science based and knowledge creation and diffusion increasingly has become a complex process spurred by different actors on various stages of the supply chain including the users of the new technologies. At their beginning formal scientific knowledge, individual as well as collective knowledge plays an important role. Much of this knowledge, including the definition of problems, is implicit and diffuse – in the sense that Polanyi (1956) defined tacit knowledge. Therefore, innovations do usually share an element of the unexpected, accidental, even if they are developing along a specific technological trajectory and true uncertainty in the sense of Knight (1921) matters.

The Innovation Systems approach has achieved high visibility and considerable political influence. This might be one reason why it has also attracted much criticism. Rammert (2002), for example, criticizes the dominant system-oriented approaches by claiming that they lack answers to important questions concerning the micro-foundations of innovations. He argues that (1) the processes of institution-building cannot be explained to the extent that the activities of individual and collective actors are not adequately considered (see also Nooteboom, 2008 on this point); (2) In relation to the missing actors' perspective the processes by which innovation activities shape technologies are not well conceptualized; and (3) the formation process of habits and institutions is neglected, though institutions, norms and habits play a basic role in this approach (e.g. Nooteboom, 2002). As a corrective, Rammert (2002) suggests that we use an action-based theoretic approach that combines formational and institutional aspects. The challenge is to combine elements of structural and action theory oriented thinking to answer the question, "How are innovations generated, shaped, and institutionalized by innovation activities that are widely distributed in heterogeneous innovation systems and networks?" The network metaphor, as used by Rammert and others,[2] seems particularly useful for highlighting the role of innovation and change. However, it also tends to downplay the structural determinants of innovation as well as the possibility that technological trajectories can be stable over extended periods of time.

In sum, recent theorizing about innovation suggests that it is increasingly difficult to predict and influence the process of innovation by using simple measures. While many industry contexts call for innovation oriented policies, in part because other macro-level policies have proven to be unsuccessful, it has become more difficult to develop and apply simple recipes. The following points summarize the changes in innovation systems:

- *Horizontal differentiation:* The strict separation between specific forms of policy (e.g., technology policy, industrial policy) has been eroding, in particular the dichotomy between research policy and education policy is lost.
- *Vertical differentiation:* There has been a proliferation of relevant policy actors. In the field of energy production, the behavior of local and regional governments as well as social movement organizations can be crucial.

[2] E.g. Asdonk et al. (1991), Kowol and Krohn (2000), and Rammert (2000a, 2000b), Pyka (2002).

- *Diversifiation of policy instruments and an increasing importance of the diffusion-oriented policy design[3]:* There is a clear tendency away from sector specific subsidies and equivalent industry-specific arrangements towards an emphasis on "collective learning" and interactions connecting firms and industries.
- *From artefacts to services:* There has been an increased focus on linking services and other non-industrial activities to different industrial segments. Not only are services becoming more important for innovation, but the boundaries between services are becoming increasingly blurred.
- *Extended causal model of the targeted field:* There is growing recognition that the introduction of new technologies alone will not solve economic and social problems. Learning and knowledge are concepts that are tied to people, and if the people cannot keep pace, there is little point in having access to new technologies.
- *New access points:* There has been a change in focus with respect to the development of technology from the supply side towards the demand side. Given that innovation and learning processes are interactive and involve both knowledge of technology and knowledge of user needs, it is appropriate to argue that the one-sided focus of technology policy on the producer side must be abandoned in favor of a more balanced approach (cp. Lundvall, 1999).

The complexity and uncertainty of the setting in which innovation processes are embedded makes it very difficult to predict the likely success of innovations or to identify even in very general terms the requirements for the successful implementation of innovations. We propose that the Cross Impact Method discussed below is a way to deal with such demands in this complex and volatile environment. In this study, we assembled several experts in various fields of innovation research and policy, as well as experts in the specific targeted field – in the present case, energy technologies – to systematically develop a profile of likely interdependencies among the actors in the technology system and to identify causal chains that might produce successful innovations. Given that innovation research is an interdisciplinary field, using the knowledge of experts from diverse areas of inquiry seems an appropriate approach to capturing the

[3] See Ergas (1987) and Cantner/Pyka (2001).

heterogeneity of actors and knowledge in high-technology environments in which it is normally difficult to create synergies.

## 3. Energy economics and new technologies

Fossil fuels are currently the main energy source in Germany. Consumption of these kinds of fuels is closely linked to environmental problems such as those related to global warming. Because fossil fuels are in limited supply, there are also concerns about resource scarcity. To meet the challenges of global warming and resource scarcity it is necessary to improve existing technologies and to develop new ones. There are also needed changes at the institutional and political level, as well as in the behavior of individual consumers. Our analysis below focuses on five new technologies that address these concerns, demonstrating the linkages between different parameters (e.g., types of innovation policies) and the uses of these technologies.

### *3.1 Advanced fossil power plants*

Fossil power plants (lignite, hard coal, natural gas) produce currently a share of approximately 60 % of electricity supply in Germany. Their share is expected to continue to rise due to the intended nuclear phase-out. Technical innovations in this field are aimed primarily at improving efficiencies associated with fuel savings, cost reductions, preservation of resources, and emission reduction. For all types of power plants, improvements can be expected in three areas: (1) Improvement of the combustion flow, (2) stream technical improvements of the turbine, and (3) utilization of the combined gas and steam turbine technology. Efficiency improvements by the year 2020 for coal-fired power plants are expected to be in the range of 53% to 60%; for gas-fired power plants efficiency improvements are estimated to be about 63%. Further effects are substantial. Fuel costs and greenhouse gas emissions per unit of electricity produced may decrease by approximately 30% when reaching the efficiency of 55 % of today’s typical hard coal power plant.

*3.2 Small combined heat and power plants (CHP)*

In contrast to conventional power plants, CHP stations are generation units designed to produce electricity and usable heat simultaneously. In our study, we focus on the analysis of CHP stations with a capacity of up to 100 kWel. The technology portfolio includes district heating power stations, stirling engines, fuel cells, and generation units using micro-gas turbines. Small CHP stations are particularly suitable for use in buildings with constant heat demand (e.g., hospitals, small and medium sized enterprises). Currently, small CHP stations are used mainly for bigger building units or buildings with high demand for heating. It is expected that smaller units (< 5 kW), which can also run reasonably well in small single family homes, will be available soon. Because of high costs and numerous other problems of a technical (e.g., down-sizing CHP stations, plant reliability) and institutional (e.g., standards and procedures in connecting small CHPs to the grid) nature, few small CHP-stations are currently being installed in Germany. Once these problems are solved, small CHP plants may play an important role in a future energy system.

*3.3 Energetic optimization of buildings and building techniques*

The energetic optimization of buildings and building techniques ranks among the most important energy-saving potentials in Germany. While typical heating values for old buildings are approximately 250 kWh/(m2a) and today's legal requirements are about 75 kWh/(m2a), trend-setting concepts such as “passive and 3-litre” buildings require only 15 to 30 kWh/(m2a). "Zero-Energy-Buildings" are technically feasible, but still uneconomical. Improvements require only technical innovations (e.g., material-technical innovations, combined heating, ventilation and cooling systems, light-steering systems, measuring and automatic control) and non-technical innovations (e.g., monitoring of consumption, training and education, private contracting, information and motivation). Innovations in planning instruments are expected to produce savings with regard to the renovation of old buildings, the use of passive solar energy use, and the use of artificial lighting, cooling, and ventilation. In the analysis below, we will incorporate knowledge of the impact of innovations in the energetic optimization of buildings and building techniques on the application possibilities of internal combustion engines.

*3.4 Electricity and heat storage technologies*

Storage technologies are technologies designed to store excess electricity or heat to provide stored energy when demand peaks. Hydroelectric storage plants and interseasonal heat storage units permit the storing of energy for extended periods of time. These technologies normally have capacities large enough to supply electricity for at least several hours. Other storage technologies like batteries, capacitors, superconducting magnetic energy storage (SMES), compressed air energy storage (CAES), and flywheel energy storage units have substantially lower capacities and have only short-term usage. At the moment, many of the storage technologies are still in the development or pre-commercial phase. As the amount of electricity produced from wind power plants increases, storage technologies will become increasingly important.

*3.5 Load management*

Load management aims at improving the utilization of power plants by reducing electricity demand at peak times. It also helps to reduce the impact on the electricity grid. Load management includes spreading the load caused by production activities more evenly and shutting down electrical appliances in private households whose use is not time critical. These measures often require intervention at a technical, organizational, and institutional level. The increased use of renewable energies expected in Germany will lead to a higher load for the grid. Additional load management measures will be necessary to balance the grid and to avoid shortages.

The technologies described above are directly or indirectly related. For example, the increased use of small CHP power plants will reduce the demand for fossil fired power plants. On the other hand, the increased use of decentralized CHP stations may induce the development of new load management measures. Like load management techniques, new storage technologies can also be used to balance the grid. Storage technologies can also be employed to improve the utilization of advanced fossil fired power plants, which can reduce production costs. A decrease in the heating demand of private households made possible by optimization measures will limit the use of small CHP stations. On the other hand, the use of optimization measures may be influenced by the availability of new heat storage technologies. The objective of the cross-impact methodology described below is to identify the nature of these interactions.

## 4. Cross-impact methodology

A comprehensive understanding of the issues identified above requires an examination of the interdependences among the main technological, political, and socio-economic factors, as well as an analysis of the implications. This task is fraught with several difficulties. In particular, the key factors span across disciplinary boundaries and produce a multidisciplinary impact network. Many of the linkages can be described only on the basis of qualitative judgments. These do not lend themselves to mathematical specification, rendering the use of conventional formal network analytic procedures impossible. On the other hand, the human brain is not well-suited to analyze a system of more than a few interacting factors (Brockhoff, 1977). In the present case, a qualitative methodology supported by a systematic interdependence analysis is the most appropriate approach.

An adequate approach can be found in a group of methods used in technology foresight, technology assessment, and scenario analysis. Cross-impact analysis was introduced forty years ago to analyze the implications of factor interdependence in technology development and its underlying political, social, and technological relationships (Gordon and Hayward, 1968). The basic idea of cross-impact analysis is to gather judgments – usually through expert solicitation – concerning the impact of each factor on each of the other factors, to arrange these judgments in a "cross-impact matrix", and to use these matrix data then for an assessment of the likelihood of certain factor combinations ("scenarios") occurring. Several method variants were developed in the years that followed (e.g., Kane, 1972; Duperrin and Godet, 1975; Enzer, 1980; Honton et al., 1985). The proliferation of publications on method applications has continued in recent years (Cho and Kwon, 2004; Boehringer and Loeschel, 2005; Millett and Zelman, 2005; Mueller, 2005; Hayachi et al., 2006; Lang et al., 2006; Scapolo and Miles, 2006; Banuls and Salmeron, 2007a,b), indicating persistent interest in judgment-based system analysis methods in a variety of scientific fields. However, it is somewhat surprising that genuine innovation issues have rarely been investigated using cross-impact analysis, even though technology forecasting is a widespread application context of this method. An exception is the study by Schuler et al. (1991) who compared the economic effects of process innovations and product innovations in the Canadian softwood lumber industry.

The cross-impact method variants differ in their use of judgments and analysis algorithms. Some of them employ quantitative data and procedures, whereas others prefer a more qualitative approach. We selected for this study a recently proposed method variant, cross-impact balance analysis (CIB) (Weimer-Jehle, 2001, 2006, 2008) for several reasons: (1) its qualitative orientation with respect to judgments and evaluation procedure fits well with the data restrictions we face in this study; (2) it reconciles a transparent, non-blackbox logic with a system-theoretical foundation; and (3) several previous applications have demonstrated that this method yields reasonable and useful results (Foerster 2002; Foerster and Weimer-Jehle, 2003; Aretz and Weimer-Jehle, 2004; for recent applications of CIB, see also Schweizer, 2007; Renn et al., 2007, Renn et al., 2008).

The basic approach of CIB is to understand a set of interdependent factors as a network of nodes and directed linkages (arrows). The nodes describe the factors (frequently called "descriptors" in cross-impact analysis), while the arrows represent impact relations. In the general form of CIB analysis, each factor can occupy one of several states which may be ordinal (e.g., low, medium, and high currency exchange rate) or non-ordinal (e.g., government run by party A, party B, or party C). In the present study, we chose a simplified factor type with binary state structure: each factor may be active or not active. We note that in reality many influence factors can display a larger variety of states. For example, "user networks" as an influence factor in innovation systems (section 6) can be tightly or loosely linked, they can be latent (more than "inactive" but less than "active"), and they can include the majority or only a minority of users. The reduction of this potential complexity to the description "active/present" or "not active/not present" clearly represents a considerable simplification. However, it helps to limit the number of necessary judgments and thus the workload for the experts, it keeps the model clear, and it forces the focus on the essential basic aspects of the system. The analysis showed that, despite its simplicity, using binary factors leads to a system with complex behavior, making it possible to arrive at nontrivial conclusions (section 7).

In our analysis, each impact relationship is characterized by its sign (positive = promoting impact; negative = inhibiting impact) and by its strength (0 = no impact; 1 = weak impact; 2 = medium impact; 3 = strong impact). Depending of the nature of the factor considered, passive factors may have no impact or the opposite impact of the active state. Fig. 4.1 shows an example of a binary CIB cross-impact matrix and its system-graph.

| | A | B | C | D | E |
|---|---|---|---|---|---|
| A | | +1 | 0 | 0 | 0 |
| B | 0 | | 0 | -2 | +1 |
| C | 0 | 0 | | 0 | -3 |
| D | 0 | 0 | +1 | | 0 |
| E | 0 | 0 | +2 | -3 | |

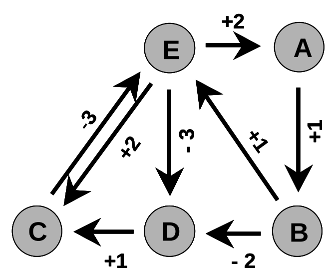


**Figure 4.1:** A simple impact network of binary factors, represented by a cross-impact matrix (left) and the corresponding system-graph (right). In the matrix, the entry +1 in the first row indicates a weak positive impact of A on B. In this example only active factors are assumed to have impacts.

The basic approach of CIB consists of three steps: (1) Scan the entire configuration space of the network; for $n$ binary factors, this consists of $2^n$ configurations; (2) for each configuration, check every factor whether its assumed state is consistent with the balance of all impacting factors; and (3) select all configurations that show no internal inconsistency. In the example shown in Fig. 4.2, each factor is consistent with its received inputs (for example, D receives only inhibiting impacts - matching the assumption that D is passive), with the exception of factor E. Factor E is wrongly assumed to be active, although it receives strong inhibition from C, overwhelming the weak support from B. Because this configuration is not completely consistent, it must be rejected. Only configurations without any inconsistencies are accepted as a believable combination of assumptions.

The analysis yields a list of consistent configurations. In the example shown in Fig. 4.1, five out of 32 configurations meet this criterion (Tab. 4.1). The consistent configurations provide insights about the set of plausible system modes and the correlations between the factors. For example, Tab. 4.1 shows that the activity of factor E is never part of a consistent configuration. It also shows that any activity in the network is strongly correlated with an active factor C. The CIB thus uses qualitative data to perform a structural analysis. It creates the set of plausible network configurations, generates information about the prospects of factors being active, identifies the key factors of the network, and yields insights concerning the preconditions of factor activities. In the following sections, we apply the CIB concept to the interaction between innovation policies, innovation related activities in society and economy, and technology characteristics.

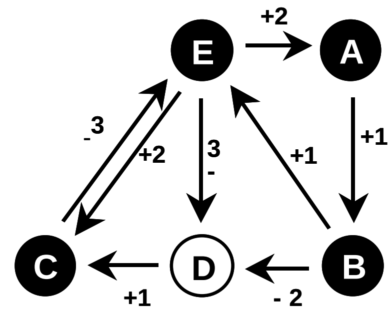


**Figure 4.2:** Example of an inconsistent network configuration. A, B, C, E are active factors, D is passive.

**Table 4.1:** Consistent configurations of Fig. 4.1. "-BC--" indicates active factors B and C, all other factors are inactive.

| |
|---|
| ----- |
| ABC-- |
| --C-- |
| -BC-- |
| --CD- |

## 5. Procedural aspects of the methodology

The qualitative systems model described here is based on expert judgments on key factors and their interactions. The method for soliciting these judgments should be suitable to yield a reliable qualitative description of the topic. To meet this requirement:

- experts were consulted who are recognized authorities in their field; they provided valid insights about the state of knowledge in their respective discipline;
- we insured that the judgments were more than the subjective opinion of a single expert; judgments were made by a peer group of experts, in order to obtain a high degree of inter-subjectivity;

- we insured that the judgments were not *ad hoc* guesses based more on prejudice than insight; judgments were made in the context of several workshops, which allowed plenty of peer discussion and analysis;

- we assembled an interdisciplinary expert panel to cover the variety of knowledge bases necessary to understand all relevant viewpoints on the issue investigated.

- we encouraged peer discussion as an instrument of quality assurance. The panel was sufficiently small to permit intense and fair interaction among all members.

We worked with a panel of 8 experts. Four of them were energy experts with substantial experience in energy technology assessment, energy economy, and energy policy. Four innovation experts covered policy research, organizational research, institutional research, and innovation economics. In addition, a two-person project team prepared, guided, and evaluated the meetings. Group discussions aimed for consensus, although the method used permitted dissenting voices as well. A consensus vote was achieved for nearly all judgments made.

The panel met for three all-day workshops between October 2004 and spring 2005. In the first workshop the method, the goals of the analysis, and the framework assumptions were discussed. The key factors of a sectoral innovation system were identified by the experts and the five technology examples were selected. Following the first workshop, the project team prepared short essays about the technologies and key factors (descriptors) in order to ensure that all panel members had a common understanding of the issues.

The purpose of the second workshop was to assess the interactions of the key factors in a sectoral innovation system. This exercise yielded the cross-impact matrix discussed in section 6.1 and shown in Table. 6.1. After the workshop, the matrix was evaluated using the CIB method in order to understand the basic implications of the data. An evaluation report was prepared and delivered to the experts. Several model calculations (cf. section 6.4) were performed as well.

In the third workshop, the experts discussed the evaluation report. Furthermore, they assessed the success conditions of technology diffusion, the technology properties, and the impulse transfer between different sectoral innovation systems. The project team then evaluated the by now completed qualitative model, prepared a final report, and sent it to the experts for review. Over the entire course of the exercise, the milestones were presented and discussed during several MEX meetings with the scientists of the larger frame project. The final results were presented at the final MEX public workshop in June 2005.

## 6. The qualitative systems model

In this section, we describe the basic ideas and the structure of the systems model which resulted from the expert workshops. The model is not intended to be a numerical systems model. It is qualitative in nature and attempts to reflect the system's interdependencies more by its structure than in terms of mathematical relationships. Nevertheless, qualitative conclusions can be drawn regarding plausible scenarios of system development, systemic implications of the interactions within the system, correlations between events, structural preconditions for the occurrence of events (e.g., the diffusion of a technology) and the success of interventions (e.g., technology policies). In contrast to a numerical model, the qualitative model describes the system in a rough, stylized manner. On the other hand, this enables a broad view on the issues, including "soft factors" and relationships for which a mathematical modeling would not be adequate.

The basic structure of the model is shown in Figure 6.1. First, we distinguish between various technological options to enhance the energy system's efficiency. Each option is represented by a set of interdependent factors such as policies, corporations, their social context, and technology properties. We conceptualize this set as a sectoral innovation system (section 6.1). The diffusion of the technology will depend, among other things, on favorable circumstances in the sectoral innovation system. Therefore, a crude model is needed to identify the preconditions of technology diffusion (section 6.2).

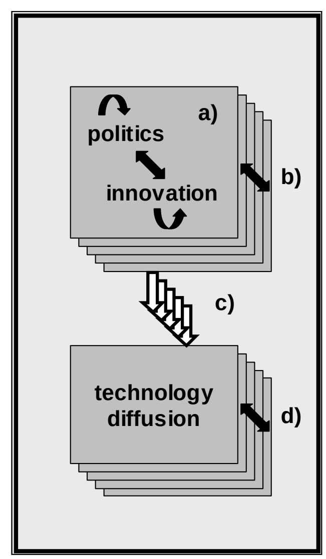


**Figure 6.1:** Basic structure of the qualitative model

In a second step, we consider the different technologies. The system described in sections 6.1 and 6.2 defines a generic pattern of the internal interactions of a sectoral innovation system. It was used as a template for the five energy technologies under consideration in this study (section 3), creating a stack of five system layers (Figure 6.1). Although each layer is based on the same generic pattern, they are not identical: Technology properties are part of the sector model, and their differences specify the layers. The model includes two types of interactions: (1) activities in the innovation system of one technology layer may stimulate activities in another layer, and (2) the diffusion of one technology may enhance or inhibit the prospects of other technologies.

### *6.1 Interdependence in a sectoral innovation system*

Panel discussions in Workshop I identified 13 descriptors as key factors of a sectoral innovation system. They belong to three domains: policies (5 descriptors), innovation context (5 descriptors), and technology characteristics (3 descriptors).

*Policies:* The experts identified indirect economic incentives, direct support policies, regulatory initiatives, technology targets, and emission regulations. (1) Indirect economic incentives, intended to elicit and support socially desirable activities, include tax incentives for research related activities, hiring research personnel, and entrepreneurship initiatives. (2) Direct support and cluster policies are intended to stimulate research and development in targeted sectors or technologies, based on the assumption that the content and objectives of such policies can be defined clearly. (3) Setting technology targets is an important aspect of a regulatory instrument, such as specifying the contribution of using X percent of non-fossil energy resources until a specific date. (4) Emission regulations in general are also an important part of the arsenal of regulatory policies. They are intended to reduce uncertainties and to influence consumption behavior directly through binding directives and sanctioning non-compliance. (5) Diffusion policies, normally without economic incentives, support the adaptation of innovations, such as support for the installation of models to demonstrate the economic feasibility and using information campaigns to influence behavior.

*Innovation context:* The most important context variables include application oriented R&D, support coalitions, user networks, service oriented corporate strategies, and the structure of actor networks. (1) Application oriented research denotes activities that are directly related to the development of a specific innovation. (2) A support coalition is defined as a group of actors who support the successful adaptation of a technological system in the market (e.g., through pilot projects). (3) User networks include experienced, highly demanding, or lead users. They can play a decisive role in the development and adaptation of innovations, given that they possess first-hand knowledge of actual problems, needs, and demands. (4) Service oriented company strategies are especially conducive to innovation, such as switching from the sale of electricity to servicing lighting in buildings and on streets. (5) The structure of actor networks may be highly heterogeneous, combining actors from various arenas and with different interests and access to different resources (e.g., in economy, polity, and science), or they may be homogeneous.

*Technology characteristics* include complementarity, sectoral industry characteristics, and service potential. (1) Technological complementarity exists when the success of an innovation in the market is easier to achieve if the underlying technology fits well into existing systems, architectures, and daily practices. (2) Sectoral characteristics include foremost the degree of vertical integration, that is, the degree to which companies perform several activities along the value creation chain in-house. (3) Service potential refers to the possibility that companies develop service oriented strategies, depending on the suitability of a given technology.

In Workshop II, the experts assessed the mutual influence of the descriptors in the form of cross-impact judgments (Table 6.1). The descriptors are defined as binary variables: the issue exists or it does not exist. Intermediate states were omitted for reasons of simplicity. A positive impact of descriptor A on descriptor B means that the occurrence of A will enhance the prospect of B occurring, and will inhibit the prospect of B’s non-occurrence. Vice versa, non-occurrence of A will have the opposite effect. Exceptions are the cross-impacts shown in italic in Table 6.1. In such cases, the non-occurrence of a descriptor has no impact. The technology characteristics descriptor “service potential” is not included in the matrix. Its impact is modeled indirectly, by stating that the impacts of row “SO” are valid only for technologies with service potential, otherwise they are zero. Furthermore, the descriptor “SO” was set to be passive for technologies that do not have service potential.

**Table 6.1:** Impact network of a sectoral innovation system. Row elements are impact sources, column elements are impact receptors. Example: the element (row: IEI / column: RD) = 1 indicates that indirect economic incentives enhance weakly application oriented research and development.

| | IEI | DC | TT | ER | DP | TC | VI | RD | SC | UN | SO | HN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Policies:** | | | | | | | | | | | | |
| **IEI: Indirect economic incentives** | | *-2* | | | *1* | | | 1 | | 1 | 1 | 1 |
| **DC: Direct support + cluster policies** | *-3* | | *-2* | | | | | 2 | 3 | 2 | 1 | 1 |
| **TT: Technology targets** | | *-2* | | | | | | 3 | | 1 | -1 | |
| **ER: Emission regulations** | | | | | | | | 1 | | | 2 | |
| **DP: Diffusion policies** | | | *1* | | | | | 2 | 1 | 3 | *1* | 2 |
| **Technology characteristics:** | | | | | | | | | | | | |
| **TC: Technology complementarity** | | | | | | | | 1 | | 2 | | 1 |
| **VI: Vertical integration (sectoral characteris.)** | | | | | | | | | -1 | | | |
| **Innovation context:** | | | | | | | | | | | | |
| **RD: Application oriented R&D** | | | | | | | | | 1 | 1 | | |
| **SC: Support coalitions** | *3* | *3* | *2* | *3* | *2* | | | 1 | | 2 | 1 | |
| **UN: User networks** | | | | | | | | | 1 | | 2 | -1 |
| **SO: Service oriented company strategies** | | | *-1* | *2* | | | | 3 | | 1 | | 1 |
| **HN: Heterogeneity of the innovation network** | | | | | | | | -2 | -2 | | 1 | |

Among other things, the cross-impact judgments address mutual impacts between policy descriptors as well as impacts of corporate and social stakeholders on policy. These “policy impacts” reflect the observation that some policy combinations have been more popular in the past than others. They also stem from the observation that stakeholders have successfully demanded certain policies that support their goals. The policy impacts enable the model to produce policy patterns which are consistent with such experiences. At the same time, they prevent the model from exploring the possibility that there are better policy patterns than those suggested by previous policy experience. Therefore, model calculations were performed in two variants: “external politics” (all impacts on/between policy descriptors were deleted) and “embedded politics” (all impacts, including impacts on/between policy decisions, were considered). Furthermore, the model was parameterized by three descriptors describing technology characteristics. These differ between technologies and give the resulting impact network a technology-specific character. The expert judgments concerning technology characteristics are shown in Table 6.2.

**Table 6.2:** Expert judgments on technology characteristics. In order to deal with intermediate statements without changing the overall design of the model, the following assignments were used in the model calculations: no/poor: exist not, yes/very good: exist, good/partial: exist, with half cross-impacts of the descriptor.

| | Load management | storage techniques | Advanced fossile fuel power plants | Small CHP | Buildings | |
|---|---|---|---|---|---|---|
| **Technology complementarity** | **poor** | **very good** | **very good** | **good** | **very good** | |
| **Vertical integration (sector char.)** | **no** | **no** | **yes** | **no** | **no** | |
| **Service potential** | **yes** | **partial** | **no** | **yes** | **yes** | |
| | | | | | | |

*6.2 Success conditions in the sectoral innovation system*

In the next step to develop a qualitative innovation model, the experts were asked to assess the necessary preconditions for a successful innovation and the diffusion of a technology. The experts were requested to weigh the key factors according to their importance. Ten points were attributable for each technology. Finally, the experts estimated how many points must be accumulated to reach the success threshold. The threshold reflects the overall difficulties of the innovation and diffusion process of the respective technology. The consensus results of the expert panel are shown in Table 6.3. The preconditions form patterns typical for each technology.

**Table 6.3:** Weights of the success conditions and diffusion thresholds.

| | Load management | Advanced fossile fuel power plants | Small CHP | Storage techniques | Buildings |
|---|---|---|---|---|---|
| Indirect economic incentives | x | x | x | x | xx |
| Direct support + cluster policies | | x | x | x | x |
| Technology targets | | x | x | | |
| Emission regulations | | xx | | | x |
| Diffusion policies | x | | x | x | x |
| Application oriented R&D | xx | xxx | xx | xxxx | x |
| Support coalitions | xxxx | | xx | x | |
| User networks | x | | x | | x |
| Service oriented company strategies | x | | x | | xx |
| Heterogeneity of the network structure | | xx | | xx | x |
| **Diffusion threshold** | 7 | 6 | 8 | 8 | 6 |

*6.3 Impulse transfer among innovation sectors*

Competing technologies can play various roles in the final success of a specific development. Innovation research has repeatedly shown that incumbent technologies have important advantages when compared with "new" technologies or novel developments. This has been discussed, for example, with respect to "path dependency". For a specific technology to be successful, a variety of contingent factors such as timing need to be considered. In an area of converging technologies, developments might also be affected by changes in a common knowledge pool. In other words, progress in one technology might advance or hinder developments in other technological fields.

The model includes a simple mechanism to account for impulse transfer. Each technology layer is coupled with other layers by a positive or negative transfer coefficient. The descriptors impact not only the other descriptors of the same technology layer but also the descriptors of the coupled layers, and thus superpose the internal impacts. The overall strength of layer coupling is handled as a parameter in the model calculations. The structure and polarity of the transfer constants among the layers were assessed by the expert panel. The results are shown in Table 6.4.

**Table 6.4:** Consensus in the expert panel concerning the impulse transfer coefficients between the sectoral innovation systems of five technologies. The coefficients express the relative strength and orientation of the links.

| | Load management | Storage techniques | Advanced fossile fuel power plants | Small CHP | Buildings |
|---|---|---|---|---|---|
| **Load management** | - | +3 | 0 | 0 | +1 |
| **Storage techniques** | 0 | - | +1 | +2 | 0 |
| **Advanced fossil fuel power plants** | +1 | 0 | - | 0 | 0 |
| **Small CHP** | +2 | 0 | -1 | - | 0 |
| **Buildings** | 0 | 0 | 0 | 0 | - |

### *6.4 Market interaction of technologies*

The market success of a technology is often affected by the market success of another technology. If two technologies are complementary, the success of one technology will also increase the attractiveness of the other one. If they compete in the same market, the technology which is more profitable will limit the diffusion of the other. In contrast to the linkages between factors analyzed above, the correlations between technologies can be assessed numerically. For this study, we selected the energy system model IKARUS to assess linkages at a technological level. The IKARUS model is a dynamic linear optimization model mapping the energy system of the Federal Republic of Germany in the form of cross-linked processes from primary energy supply to energy services (Martinsen et al., 1998, 2003). A large number of technological options are included, together with their corresponding emissions, costs, and potential networks of energy flow. In addition, general political parameters are considered (e.g., the agreement on the phase-out of nuclear power in Germany). It is possible with this model to examine whether the market share of a given technology increases or decreases, or whether a second technology is introduced in the market. In our study, we identified the linkages between the selected technologies by modifying technology specific costs. To assess the correlations between technology A and B the cost for the technology A was changed in such a way that the same market share of technology A was reached when technology B was present or absent. The highest factor (3.9) attained with the selected technologies is represented by the factor 3. All other values are calculated logarithmically from this calibration. Table 6.5 shows the results of the CI-factor calculations.

**Table 6.5:** Cross-impacts of market interactions, as calculated by IKARUS.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| CI-Factor | -3 | -2 | -1 | 0 | +1 | +2 | +3 |
| Changes in costs | x 3.9 | x 2.5 | x 1.6 | | /1.6 | / 2.5 | / 3.9 |

| | LM | Storage | CHP | Ad. fos. fuel-fired power plants | Build. | |
|---|---|---|---|---|---|---|
| **Load management (LM)** | - | -1 | 0 | 0 | 0 | |
| **Storage techniques** | -1 | - | 0 | 0 | 0 | |
| **Small CHP** | -0.1 | -0.1 | - | +0.2 | 0 | |
| **Advanced fossil fuel fired power plants** | -1.2 | -1.2 | -3.0 | - | 0 | |
| **Buildings** | +0.8 | +0.8 | 0 | 0 | - | |
| | | | | | | |

Combining the insights discussed in sections 6.1 to 6.4 produces a qualitative model of the innovation system. For a single technology, the model consists of a cross-impact matrix with 14 descriptors (13 key factors plus the diffusion success as output variable). This type of model was used to analyze the effects of technology characteristics and policy measures in the case of a stand-alone technology without significant connections with other technologies. In the case of embedded policy, only the three technology characteristics served as input variables. In the case of external policy, the five policy descriptors were also input variables. A typical question to be analyzed with the stand-alone model is which technology characteristics and which policy measures will likely lead to a successful innovation and diffusion process. Turning on the links between the technology layers expands the model size to 70 descriptors. The complete model is expected to show whether sector linkages can improve or worsen the prospects of technologies in comparison with the stand-alone case. Details of the model analysis are reported in the next section.

## 7. Results

We next apply the CIB method to the qualitative systems model described in the previous section. For this purpose we stimulate the system using different policy patterns, identify the consistent configurations of the impact network, and compare policies with respect to their effect on the innovation and diffusion descriptors. Considering the qualitative nature of the model and the method of analysis, we focus on qualitative results and insights. To accomplish this, we make full use of CIB's capacity for reconstructing the causes of any result by back-tracing the impact flows within a given configuration.

### *7.1 Lesson I: Diffusion success is not easy to achieve in the model*

Without policy (i.e., every policy descriptor is inactive) there is no consistent configuration leading to active diffusion; the unconstrained state of the system is inactivity. Moreover, the effect of a *one*-policy-strategy is doubtful. In the case of three technologies (small CHP, storage, advanced fossil power plants), no single policy is able to create a configuration with an active diffusion descriptor. For the other technologies, only one policy (out of five policies) creates an opportunity to activate diffusion. In this case, the system possesses two configurations with and without diffusion. This means that the effect of the policy is uncertain. Success, however, is possible rather than compulsory. Indirect economic incentives are the best policy for building technologies, mainly because this type of policy has the strongest direct impact on the prospect of building new technologies. However, diffusion policy is the best fit for load management. Tracing back the reasons for this latter result reveals that the poor technological complementarity of load management (i.e., the disruptive and non-linear character of this innovation) creates disadvantages in triggering R&D activities and constructing user networks. This would require a policy with specific strengths in these respects. However, even in the best case, the effect of a single policy is uncertain.

### *7.2 Lesson II: Different technology characteristics lead to different prospects and require different policy approaches*

The analysis so far has indicated that at least a combination of two policies is required to create significant opportunities for all of the five technologies considered in this model. We applied all possible policy pairs (10) to the system and studied the outcome for each of the technologies. This showed that some technologies respond only to a few specific combinations, while others react to many policy combinations. In particular, storage and small CHP are difficult to activate: the diffusion descriptor is activated only by the combination direct support/cluster policies + diffusion policies. Advanced fossil power station technology responds to two, building technologies responds to five, and load management responds to six policy combinations (Table 7.1). Therefore, the prospects of the technologies would be very different if an arbitrary pair of policies were chosen. Direct support/cluster policies + diffusion policies proved to be the best "generic" pair of policies. It worked for all technologies, with the exception of advanced fossil power stations. The poorest performance outcome is produced by the combination "indirect economic incentives + technology targets". This combination was not able to generate, for any of the five technologies, a system configuration with an active diffusion descriptor.

The underlying reasons for each of the results shown in Table 7.1 can be identified with the help of CIB's back tracing capabilities. For example, we examined the rather surprising observation that "advanced fossil power plants" (AFP) did not respond to the otherwise fully successful policy combination "direct support/cluster policies + diffusion policies" (DC+DP). The reason for this anomaly apparently lies in the needs profile of this technology (Table 6.1). It does not benefit from support coalitions or user networks, whereas it is a special strength of DC+DP to activate these factors. This is different for the other technologies which benefit from either support coalitions or user networks, or from both. On the other hand, activating R&D is crucial for AFP, whereas DC+DP excludes the policy that has the strongest effect in this respect (technology targets). Moreover, AFP's unique lack of service potential further inhibits the R&D

descriptor. Both contribute to the result that DC+DP fails to activate R&D with respect to this technology. In short, every policy (or policy combination) generates a characteristic activity pattern in the innovation system, but the pattern of DC+DP does not match well with the pattern of AFP's needs. The key does not fit the lock.

**Table 7.1:** Effect of two-policy combinations on technology diffusion. X: policy evokes system configuration with active diffusion descriptor. (X): policy evokes both configurations with active and with inactive diffusion descriptor. -: policy evokes configuration with inactive diffusion descriptor. See Fig. 6.2 for abbreviations.

| | DC + DP | DC + ER | IEI + DC | TT + ER | IEI + ER | IEI + DP | TT + DP | DC + TT | ER + DP | IEI + TT |
|---|---|---|---|---|---|---|---|---|---|---|
| **Load management** | X | X | (X) | - | - | - | (X) | (X) | (X) | - |
| **Storage techniques** | X | - | - | - | - | - | - | - | - | - |
| **Advanced fossil fuel power plants** | - | (X) | - | X | - | - | - | - | - | - |
| **Small CHP** | X | - | - | - | - | - | - | - | - | - |
| **Buildings technologies** | X | (X) | (X) | - | (X) | (X) | - | - | - | - |

*7.3 Lesson III: More intensive political action is not always helpful*

The prospects for success generally increase if additional policies are applied in the model. However, we also identified several cases in which the application of an additional policy turned out to be counterproductive. For example, load management's diffusion success is possible if the policy combination "ER+DP" is applied (Table 7.1), but supplementing this policy pattern with "Indirect economic incentives (IEI)" would eliminate this prospect. The reason is that the policy combination "ER+DP" is not conducive to the development of homogeneous innovation networks. Under these conditions, the additional use of IEI favors heterogeneous networks, hindering the emergence of support coalitions – which are a major success prerequisite in the case of load management.

Another example of counterproductivity in the system is the effect of technology targets (TT). As mentioned in section 7.1, IEI is able to generate a success configuration for building technologies. While the IEI policy is partly successful when working on its own, the policy pair IEI and TT fails completely (Table 7.1). Apart from several supporting effects, TT has one disadvantage: it discourages companies from developing service-oriented strategies (Table 6.1). This is decisive in this case because service-oriented company strategies play an important role in the diffusion of building technologies (Table 6.1).

A combination of all five policies – which is probably a rather unrealistic scenario – will eventually lead to robust diffusion of each of the five technologies.

### *7.4 Lesson IV: Pathways to innovation and diffusion success differ in robustness*

The results in Table 7.1 seem to suggest that different policy combinations have a comparable impact on a given technology. Closer inspection, however, reveals that they usually differ with respect to the robustness of diffusion success. We examined all successful combinations of technologies and policy patterns as shown in Table 7.1. In each case, we switched off a single innovation factor (RD, SC, UN, SO, or HN) by an external impact pulse – thus simulating an inhibition of this factor due to unfavorable environmental circumstances – and examined whether this would inhibit successful diffusion or whether the system would remain productive. If a factor proves to be indispensable for successful diffusion, it is called a critical factor. In some cases, we found only one critical factor (Table 7.2). In other cases, success proved to be less robust and was found to be vulnerable to the failure of various factors. In some cases, success was so precarious that it could be eliminated through manipulation of any innovation factor.

**Table 7.2:** Critical success factors for technology innovation and diffusion. The entry "SC" in the cell "Load management" / "DC+DP" indicates that success prospects are completely lost if external circumstances prevent the emergence of support coalitions. For most combinations of technology and policy pattern there is more than one critical factor. The failure of a single critical factor is sufficient to destroy the success prospects in these cases. The symbol ~~HN~~ means that not the presence but the absence of the factor "Heterogeneity of innovation networks" constitutes a critical success factor in this case. See Tab. 6.1 for abbreviations.

| | DC + DP | DC + ER | IEI + DC | TT + ER | IEI + ER | IEI + DP | TT + DP | DC + TT | ER + DP | IEI + TT |
|---|---|---|---|---|---|---|---|---|---|---|
| **Load management** | SC | RD<br>SC<br>SO<br>~~HN~~ | RD<br>SC<br>UN<br>SO<br>~~HN~~ | - | - | - | RD<br>SC<br>~~HN~~ | RD<br>SC<br>UN | RD<br>SC<br>UN<br>SO<br>~~HN~~ | - |
| **Storage techniques** | RD<br>SC<br>UN<br>SO<br>HN | - | - | - | - | - | - | - | - | - |
| **Advanced fossil fuel power plants** | - | RD<br>SC<br>~~HN~~ | - | RD<br>~~HN~~ | - | - | - | - | - | - |
| **Small CHP** | RD<br>SC<br>UN<br>SO | - | - | - | - | - | - | - | - | - |
| **Buildings technologies** | SO | RD<br>SC<br>SO | SC<br>SO | - | SO | UN<br>SO | - | - | - | - |

*7.5 Lesson V: Technology linkages stimulate the emergence of technology sets in the model*

Innovation and diffusion activities in a technology sector may affect the activities in other technology sectors both through market interactions and innovation impulse transfer, as discussed in sections 6.3 and 6.4. This produces a technology subset with mutually supporting effects. Assuming that the components of technology linkages (market interactions and innovation impulse transfer) are of comparable strength, we found the technologies Storage techniques / Small CHP / Building technologies to be a triad of mutual promotion and stabilization. Innovation impulse transfer links storage techniques with small CHP (Table 6.4) and market interactions link building technologies with storage techniques (Table 6.5). On the other hand, storage techniques and small CHP exclude load management and advanced fossil power plants from the set because of their competitive implications. Still, innovation and diffusion of these technologies must be stimulated by political measures, as described above, although these policy impulses will be further supported through technology linkages.

*7.6 Lesson VI: The usual policy patterns do not match well the needs of innovation and diffusion in the model*

The cross-impacts in the left-hand side of the matrix in Table 6.1 show the experts' view that (1) policy makers usually prefer certain combinations of instruments, and (2) pressure may come from social actors who support certain policy instruments while trying to prevent others. These cross-impacts were omitted in our previous model analysis in order to get an idea of what kind of policy would be able to achieve success if policy makers were able to shape their policy in an independent and unbiased way.

However, if we assume that policy actions follow the traditional preferences in combining instruments, we find that innovation and diffusion are less likely to succeed. Policy-policy-impacts sort out 20 policy combinations (out of $2^5$=32 possible combinations) which are not consistent with policy traditions. The remaining 12 combinations contain a disproportionately high number of unsuccessful combinations (Table 7.3). Therefore, the average traditional policy combination shows a poorer performance than a randomly chosen combination. The size of this effect differs across the five technologies. The quota of fully or partly successful policy combinations declines marginally in the case of "advanced fossil fuel power plants" from approximately 53% to 50%, whereas the same quota declines significantly in the case of "small CHP" from approximately 41% to 17%.

Furthermore, social feedbacks mechanisms may evoke policy intervention. The panel experts expected this outcome to arise especially in the presence of "support coalitions" and "service oriented company strategies". Their presence may lead to chains of events. For example, an initial policy may be insufficient to create adequate conditions for short term innovation and diffusion success. But if the initial policy is able to evoke a key factor, such as a support coalition, it may lead to additional policy actions, and these may eventually trigger innovation and diffusion of the innovation. This outcome can be observed in the model if "feedback to politics” is included in the calculation.

**Table 7.3:** Possible policy combinations with and without policy-policy interactions. The column “Success” counts the policy combinations for which all consistent configurations include innovation and diffusion. “Failure” counts policy combinations without any successful configuration. “Mixed” contains all cases in which a policy combination evokes both success configurations and failure configurations. The entry “19” in the cell “Storage techniques” / “Failure (policy-policy-impacts omitted)” indicates that 19 policy combinations out of 32 possible combinations generate only consistent configurations without diffusion.

| | Policy-policy-impacts omitted | | | | Inclusive policy-policy-impacts | | | |
|---|---|---|---|---|---|---|---|---|
| | Total | Failure | Mixed | Success | Total | Failure | Mixed | Success |
| **Load management** | 32 | 12 | 10 | 10 | 12 | 6 | 3 | 3 |
| **Storage techniques** | 32 | 19 | 1 | 12 | 12 | 8 | 0 | 4 |
| **Advanced fossil fuel power plants** | 32 | 15 | 1 | 16 | 12 | 6 | 1 | 5 |
| **Small CHP** | 32 | 19 | 2 | 11 | 12 | 10 | 0 | 2 |
| **Buildings technologies** | 32 | 10 | 6 | 16 | 12 | 6 | 1 | 5 |

## 8. Conclusion

The aim of this paper was to demonstrate the usefulness of a cross-impact methodology for understanding the prerequisites of successful innovation processes. Our analysis of innovation in five select energy technologies has shown that this method generates a number of interesting results. The Mex-5 exercise has produced several important insights that are useful for theory building in the area of innovation and for developing policy programs intended to stimulate and support innovations. Based on the panel expert statements and the scenarios developed with specialized software, we showed that there are several viable ways to influence innovation processes.

The ability to manipulate innovation processes is important in a context and at a time when national technology or innovation policies are generally viewed as quickly becoming obsolete. This is all the more important given the unique characteristics of energy production regarding energy supply that responds to changes in climatic conditions and to policies that are developed in reaction to perceptions about global warming. Changes in the governance structure of the energy sector are driven by many forces that lead to a liberalization of markets. In many countries, the state is retreating from direct ownership and control to stimulate competition in power generation. Private R&D budgets have been declining, partly as a result of liberalization policies. Thus, the creation of new technologies and the supply of new forms of energy continue to rely on public subsidies and favorable accounting rules, while public spending on energy R&D is declining. Innovations in the energy sector are thus becoming increasingly urgent, while the mechanisms to stimulate innovations are becoming more complex.

In this uncertain environment, it is critical to understand the key forces that stimulate innovation and the factors that govern the diffusion of innovations. The findings of our analysis are fully consistent with the dominant view in contemporary innovation theory that innovation is a complex and often path dependent process, characterized by the interdependence of a variety of agents who need to interact if they are to learn and respond creatively. Our study also supports the view that there are certain sector and technology specific patterns of innovation that need to be taken into account in innovation policy. In this context, our aim was to extend existing theoretical and empirical insights concerning the development of new practices, especially with respect to institutional entrepreneurship. The scenarios we developed highlight the emergent, multilevel nature of innovation processes, as well as the role of agency in these processes.

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