Prospective Analysis of Socio-Technical and Organizational Variations: Conceptual Elements and Empirical Findings from the Innovation System for Stationary Fuel Cells in Germany

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Abstract

Although uncertainty is an inherent feature of radical innovations, there is a need in strategic decision making to explore future development options of emerging technologies. In this article we present a methodology that suggests a prospective analysis along potential socio-technical configurations of a new technology and the constellation of actors within an innovation system. Theoretically, we draw on a combined conceptual framework of technological innovation systems and transition theory. The method is illustrated by a case study on stationary fuel cells, a radical innovation in the field of electricity and heat supply.

Introduction

Radical innovations such as new technologies or products tend to develop in a non-linear way as they are subject to a complex interplay of actor strategies, institutional settings and developments in their socio-technical context. Innovation activities of actors within an innovation system may mutually reinforce each other and set in motion processes of cumulative causation. Strategic moves of powerful players can have a significant impact on the direction of search and innovation processes. Moreover, emerging technologies in adjacent innovation fields, novel market opportunities or new priorities in the political arena may also influence the innovation process. As a consequence, the development path an innovation takes cannot be predicted and surprises have to be regarded as an inherent characteristic of innovation processes.

However, innovating firms as well as innovation policy makers must prepare for potential developments in the respective field(s). They might want to know more about different applications for the novel product and how these are influenced by the progress of the innovation itself and by developments in the broader context. They might also be interested in how newcomers and incumbents position themselves with regard to the new technology or what kinds of business models might evolve under different conditions. A common way to address these kinds of questions in situations characterized by considerable uncertainty is scenario analysis (e.g. de Jouvenel 2000; Godet 1986; Hofman, Elzen & Geels 2004).

Embracing the basic idea and explorative character of scenario building, we will present and empirically apply an approach that seeks to systematically explore the development options in a selected innovation field. A distinctive feature is that this approach is theoretically based on the concept of technological innovation systems (cf. Carlsson & Stankiewicz 1995; Edquist 2005; Hekkert et al. in press) but also draws on the literature on socio-technical regimes and transitions (e.g. Elzen, Geels & Green 2004; Geels 2002; Rip & Kemp 1998). At the core of our analysis is a particular innovation field, embedded in a context that consists of socio-technical regimes, adjacent innovation fields and landscape factors. Starting with a basic analysis of the innovation system and its context, the approach identifies potential configurations in terms of socio-technical design and 'organizational structures' (actor constellations). The analysis also includes the identification and assessment of key factors for those different development options. Our empirical field is the innovation system for stationary fuel cells in Germany.[1]

Theoretical framework of the analysis

Innovation processes can be analyzed from at least two different perspectives. One may either start with an established socio-technical regime, e.g. electricity supply from centralized power stations and explore the—possibly transforming—pressures that arise from the landscape level, e.g. climate change, market liberalization, as well as from novel products and technologies (cf. Hofman et al. 2004). As an alternative, one may focus on a particular innovation field like fuel cell technology and ask which factors might propel or hinder its development, which applications may turn out to be promising, which actors will commit themselves to the innovation etc.

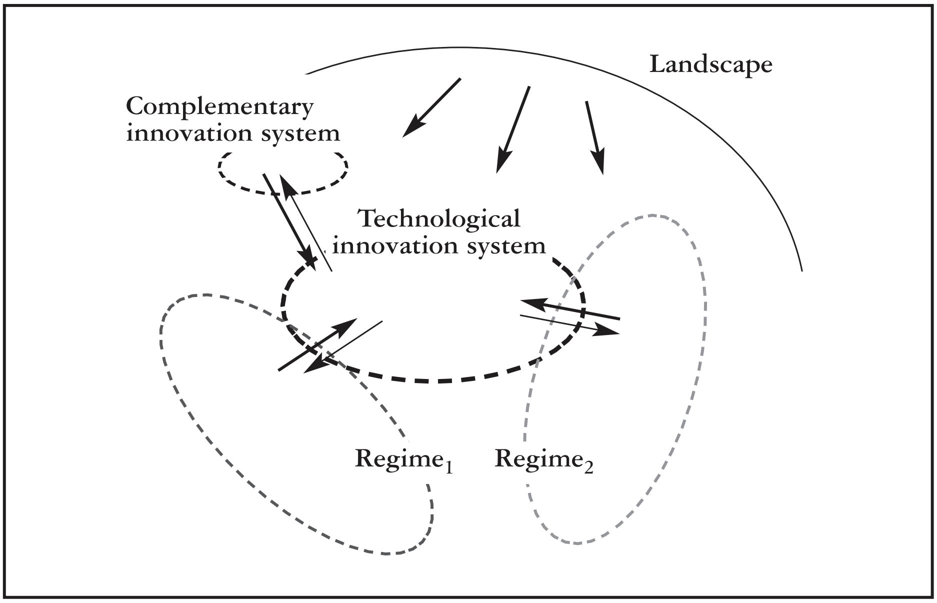
In the following, we will take the latter perspective, for which the (technological) innovation system concept seems to be a promising theoretical foundation. The innovation system is a generic concept and different variants have been applied for different purposes of analysis (see Carlsson et al. 2002; Chang & Chen 2004 or Edquist 1997 for an overview). The approach is based on evolutionary economic theorizing and highlights the importance of emerging networks and institutions as well as collective learning processes for successful innovation processes. Here, we draw on the concept of *technological innovation systems*, which we define as[2]

> a set of networks of actors and institutions that jointly interact in a specific technological field and contribute to the generation, diffusion and utilization of variants of a new technology and / or a new product.

Technological innovation systems (TIS) have a context, or environment, in which they are embedded, cf. Figure 1. This environment may stimulate or hinder the innovation processes within the system and it might also be influenced by them. As a rule, system boundaries should be defined in a way that the interactions among components within the system are more intense than the interactions between the system and its context. The environment can be conceptualized as a set of socio-technical regimes, landscape factors and other innovation fields (Markard 2006b).

Socio-technical regimes are coherent, highly interrelated and stable structures characterized by prevailing stocks of knowledge, user practices, expectations, norms, regulations etc. (Geels 2002; Rip & Kemp 1998). Regimes have emerged around established products and technologies. They usually represent barriers for the development and diffusion of radical innovations. Though different in nature, technological innovation systems and socio-technical regimes may share some actors or institutions.

Figure 1. Relationships between the technological innovation system and its context



At the landscape level, economic growth, changing factor prices (energy, labour, material, capital etc.), broader socio-political issues or social movements may influence technological innovation systems, and also existing regimes, in the form of selection pressures (cf. Smith, Stirling & Berkhout 2005). While regimes can be characterized as 'mostly external' from the perspective of the innovation system, landscape level factors are 'truly external' as they are hardly affected by the developments in the innovation system.

Finally, the TIS, which is in the focus of the analysis, might be affected by other technological innovation fields and vice versa. There are two basic modes of interaction: competition and complementation. Complementary innovations support each other, e.g. network technologies. Competition occurs when the products or technologies in two TIS serve similar purposes in similar application contexts. However, even a competitive technology may have a complementary effect if it contributes to the weakening of prevailing regimes that hinder the innovation process in both systems.

Method for the analysis of development options

Against this conceptual background, we will now explicate our method to explore future development options within an innovation system. Departing from a profound understanding of the current status of the innovation field and its environment, the idea is to elaborate on future development options with regard to socio-technical configurations and constellations in which different actors may work together. Moreover, major factors that influence the realization of these technological and organizational configurations will be identified. While these results can stand for themselves, they may also be used to sketch scenarios and alternative development paths of the innovation field (cf. Markard 2006a).

Basic analysis

The basic analysis concentrates on the innovation field or system.[3] The focus is on the current status but developments in the past or specific expectations of future innovation characteristics should also be addressed. The idea is to identify the key characteristics of the innovation. This usually includes technical aspects (e.g. functioning of the new technology, performance characteristics, application contexts, pilot projects) and socio-economic aspects (e.g. costs, market diffusion, existing niches). Ecological characteristics will also be addressed, if relevant. The innovation characteristics may be presented in comparison to established products or technologies in order to develop a profile of strengths and weaknesses and to provide further insight into the innovation potential, e.g. where and how the innovation may link up with existing technologies or structures.

With regard to the innovation field, this first module also explores which actors and actor groups are involved in innovation processes and the roles they play.[4] This part is complemented by an overview of supportive institutions like specific R&D programmes, intermediaries or legal framework conditions. Finally, innovation networks including the relationships among actors and between actors and institutions will be identified. As a result, the basic analysis provides evidence about the maturity of the innovation system and whether we can talk about an innovation system at all.

Context analysis

The aim of the context analysis is to understand the key characteristics of the environment in order to identify the most important influencing factors and linkages with the innovation system under study. With regard to socio-technical regimes, a first methodological step is the identification of regimes that have a decisive impact on the innovation, which means that their structures and prevailing characteristics determine application contexts, user practices and expectations, values, norms, quality criteria etc. What follows is an assessment of how the regimes influence the innovation under study. A further step includes a review of recent changes or development trends at the regime level in order to gain insights into the stability or potential weaknesses of prevailing regimes. Against the background of these analyses, we can also derive some rough ideas on how the regimes might react in the case of innovation diffusion.

At the landscape level, the analysis includes the current situation but should also look at trends or ongoing changes which might put pressure on the relevant socio-technical regimes. Typical aspects to be investigated are changes in socio-economic parameters such as factor prices, economic growth, demographic characteristics or cultural values, but also key issues on the political agenda (unemployment, climate change, security) or far-reaching events like wars, major accidents, catastrophes etc.

Finally, the context analysis scans other innovations, or innovation systems, in the broader area that might be relevant. The idea is to identify complementary and competing innovations (cf. section 'Theoretical framework of the analysis') and to clarify how these may influence the innovation process we are interested in.

Variation analysis

On the basis of these initial studies, the third part of the methodology deals with future development options, or variants. Here we propose to distinguish two basic dimensions along which to study variation. On the one hand, we look at different technological designs and different application areas of the novel product. On the other hand, we ask how the innovation related supply chain may be organized, i.e. how major innovation tasks may be distributed among different actors, or actor groups. Whereas the first dimension deals with variation in terms of socio-technical design, the second basically distinguishes different actor configurations in the sense of role models. We will label these two dimensions 'socio-technical' and 'organizational' variation, respectively.

As a first step, major variants will be identified and described in both dimensions.[5] Variants may already be applied in practice or hypothetical in nature. They may either co-exist or be mutually exclusive in the sense of alternatives. As a further step, a review of the most important influencing factors is carried out for each variant in order to understand the conditions of 'realization'. This assessment is closely linked to the findings from the basic and the context analysis.

Finally, potential combinations of socio-technical and organizational configurations are explored. This analytical step is based on the fact that each socio-technical configuration has certain characteristics (technical features, application contexts, potential users etc.), which require specific resources and competences of the actors involved. As a consequence, some actors or actor groups are more likely to commit themselves to a particular technological variant than others. Similarly, a particular socio-technical configuration may imply a specific interplay of actors in the sense of specific roles assigned to producers, suppliers and users.

In other words, the variation analysis represents a systematic search for coherence conditions—in technological as well as socio-economic terms. Such conditions determine the internal coherence of major variants as well as between variants. Some coherence conditions may have the character of natural laws, i.e. they remain influential whatever will happen in the future, while others might just be stable on a mid-term basis, e.g. for some years.

Innovation system analysis for stationary fuel cells

Stationary fuel cells (FC) represent a novel product in the field of electricity and heat supply. A fuel cell transforms hydrogen or natural gas into electricity and heat. In the following, we will present some selected empirical findings from a study on the innovation system for stationary fuel cells in Germany.[6] Germany has the largest fuel cell 'industry' in Europe, including about 3,000 employees in 350 firms or other organizations[7] as of 2003 (Geiger 2003). In the sub-field of stationary fuel cells, more than 500 small units (pilot and field test plants, for residential customers) and about two dozen larger units (pilot plants, for commercial customers) were planned or already installed in 2003. The majority of these stationary fuel cells is operated by utility companies.

Most of our data was obtained by the study of literature, magazine articles and firm or project specific documents. This was complemented by interviews with two experts from utility companies and one from a research institute. One of the utility experts was also asked to review and comment on the empirical findings in detail. Adjustments were made accordingly.

Basic analysis

Various types of stationary fuel cells exist today, which differ with regard to the electrolyte, catalyst materials, operating temperatures, fuel requirements etc. (cf. Carrette, Friedrich & Stimming 2001). Pilot plants and prototypes cover a variety of applications. Despite this diversity, stationary fuel cells have several innovation characteristics in common. In technological terms, they are characterized by high energy efficiency, a favourable electricity-to-heat ratio, silent operation without moving parts and low air emissions. Furthermore, fuel cells can use a variety of primary fuels such as natural gas, methanol or biogas. Due to their modular design fuel cells can supply electric power from some Watts up to several Megawatts.

With regard to the innovation process, most types of fuel cells are still in an early phase of development, i.e. they are mostly operated and tested in the context of R&D projects, pilot plants or field tests. The two most important challenges for further development are to significantly reduce system costs and to improve the lifetime of fuel cell stacks. Because of the early innovation phase, fuel cell based products involve a high degree of uncertainty. Together with a considerable need for financial investments, this results in high financial risks for actors in the field.

Stationary fuel cells can be classified as a radical innovation if the reference case is electricity production in large, central power stations (cf. Markard & Truffer 2006b). A widespread diffusion of the new technology would lead to a decentralization of electricity supply with far-reaching consequences. Moreover, fuel cells would foster integration of the markets for power and heat supply, which are mostly separated today.

Actor groups, generic roles and networks

In general, various groups of actors are active and share different innovation tasks in the field of stationary fuel cells in Germany: universities and research institutes, fuel cell manufacturers and suppliers, utility companies, installers, associations, governmental agencies, financiers and end users. Manufacturers, for example, are involved in applied research and prototype testing. They design and manufacture entire fuel cell power plants, while relying on a number of up-stream equipment suppliers. German manufacturers are business units of large firms such as Siemens-Westinghouse, Vaillant or MTU, which have their core business in traditional markets for electricity generation (Siemens), heating boilers (Vaillant), or other industries (MTU). International manufacturers such as Ballard, PlugPower, Sulzer-Hexis or UTC Fuel Cells are either start-ups or, again, sub-units of established firms, e.g. in battery manufacturing.

Utility companies, as another example, identify promising market niches and develop energy services on the basis of stationary fuel cells (e.g. in the form of contracting). For manufacturers they play a user role, while at the same time they also frequently manage the interface to the end consumers of energy. In Germany, many large utility companies like RWE, E.ON, Thyssengas or EnBW, but also some regional or local utilities are among the pioneers in the field as they operate pilot power plants at their own locations or at customers' facilities.

The relationships among actors are manifold. Among firms we find user-supplier linkages but also formal co-operations, mergers and acquisitions, strategic partnerships and marketing alliances. Two examples of such strategic partnerships in Germany are the Fuel Cell Initiative and the Fuel Cell Alliance.[8] Furthermore, numerous working groups have been established and there is also much informal interaction such as workforce mobility between firms or the exchange of information among experts at conferences etc. These activities are complemented by established 'regime' associations like the German Technical and Scientific Association for Gas and Water (DVGW), which is involved in the development of technical norms, networking, lobbying or campaigning.

Institutions

In Germany, institutions that are relevant for stationary fuel cells include publicly funded research programs, intermediary institutions, regulations and policy instruments, technical norms and the like. Research in fuel cells for example, is funded by the national Future Investment Program and by several ministries. In addition, many federal governments have set up regional R&D programmes. Intermediary institutions such as the WBZU in Ulm for education in fuel cells or the Heinz-Piest Institute in Hanover coordinate activities and facilitate the exchange of knowledge. Support for stationary fuel cells also comes from the German law on the conservation, modernization and development of combined heat and power and the electricity feed-in law. Both provide for premium payments for power generated by fuel cells. With regard to standardization and norms, finally, several initiatives are on their way to facilitate licensing procedures and the interoperability of fuel cells and local heat and power infrastructure.

Summing up, we may conclude that the domain of stationary fuel cells in Germany can be regarded as a technological innovation system with a broad range of actors, specific networks and institutions that deal explicitly with the technology. The innovation system, of course, is not limited to Germany but has an international reach—especially in terms of research and technology manufacturing. In a similar vein, there are interactions with innovation activities in other technological domains like mobile or portable fuel cells. However, activities in Germany show sufficient density and intensity that typical innovation system processes can be observed.

Context analysis

As a product, stationary fuel cells are interrelated with at least three major sectors, electricity, gas and heat supply. From a broader perspective, however, upstream steps of product manufacturing relate to sectors such as mechanical and chemical engineering, ceramic materials, electrical engineering etc. Socio-technical regimes influence production and consumption as well as technology development in probably all of these sectors. In the following, we focus on the impacts of two regimes we consider to be particularly important in our case: the regime of centralized electricity supply and the regime of decentralized heat production.

Influences of two socio-technical regimes

Electricity is typically generated in large, centralized power plants. The electrical power is brought to the consumers via high-voltage transmission lines and a sophisticated network of low-voltage power lines. Decentralized power supply from small units like stationary fuel cells does not fit well into the existing technological infrastructure. Network topologies, for example, would have to change and new devices for the control of power flows would be needed if stationary fuel cells were to cover a more significant part of power supply in the future. But organizational structures would also have to be adapted, e.g. in terms of contracting models for decentralized generation units. Electric utility companies would need to establish services and a more intense interaction with their customers, while customers would have to get used to playing a much more active role in electricity supply. While the established regime leads to a variety of significant barriers for fuel cells, the introduction of competition in the electricity sector has already weakened existing structures (cf. Markard & Truffer 2006b). Institutional changes such as regulated grid access as well as support schemes for renewable energies and highly efficient conversion technologies have already facilitated decentralized electricity generation.

In the case of heat supply, the dominant structure is a decentralized one, based on conversion units installed in every building. Oil and natural gas are the prevailing energy sources. Gas is mostly supplied by a network of gas mains, while oil comes by trucks and is stored locally. Major actors are oil producers and distributors as well as gas utility companies. Stationary fuel cells are best compatible with gas based heating because they can also run on natural gas. For that reason, gas utilities are also interested in fuel cells.

As an alternative to decentralized heat supply, a centralized district heat supply infrastructure exists in some cities with a network of heat pipelines and large heating stations or cogeneration plants, often run by local municipal utilities. Such a structure is less compatible with stationary fuel cells. We thus may interpret the situation for heat supply as two different socio-technical regimes: a dominant decentralized one where fuel cells are generally compatible, and a smaller semi-centralized one where the introduction of fuel cells might be more difficult. General compatibility, however, does not mean that there are no barriers. It is known from other innovations such as heat pumps and condensing boiler systems, which were not radical and were even economically viable, that technology diffusion was slow due to little acceptance by local installers and private customers.

Landscape level influences

Like many other technologies, stationary fuel cells are affected by macro level factors such as energy prices (oil, gas and electricity), economic growth, demographic development or the purchasing power of potential adopters. Increasing energy prices, for example, act in favour of the new, highly efficient technology, while demographic factors may determine future housing structures and whether decentralized energy supply technologies should rather address multiple or single family houses in the segment of residential customers. In a similar vein, the development of fuel cells depends on environmental concerns in the public (positive influence on technology acceptance) and corresponding policies such as CO_2 emission schemes.[9] Finally, the introduction of competition in infrastructure sectors, often in combination with the privatization of former public utility companies, represents a major international political trend, which also influences technology development in the domain of energy supply.

Complementary and competing innovations

Complementary innovations that have a stimulating influence on the innovation system for stationary fuel cells include technological, organizational or institutional novelties. With regard to technology, complementary innovations, for example, facilitate fuel cell manufacturing or the provision of related components such as devices for fuel reforming, fuel storage or supply. But also advances in the fields of mobile or portable fuel cells can have a positive impact, e.g. due to knowledge spill-over or increased public awareness and interest in the new technology.

With regard to organizational innovations, new energy services such as contracting enable utility companies as well as end consumers to gather experiences with new modes of energy supply. Such innovations facilitate the operation of stationary fuel cells even if they have been initially developed for other technologies. In a similar vein, institutional innovations such as regulations for third party access to the electricity grid or feed-in tariffs for decentralized power supply foster stationary fuel cells, although not primarily designed to do so.

In the field of heat supply, solar heating systems, heat pumps and wood-fired boilers represent competing, renewable energy based innovations that are mostly technologically mature but still in an early state of diffusion. In the area of decentralized cogeneration, stationary fuel cells compete with established products based on internal combustion engines and innovations such as Stirling engines and micro-turbines. Photovoltaic systems are a major competitor with regard to electricity production. Finally, fuel cells must also compete with higher building insulation standards, which reduce heat demand and thus render on-site cogeneration less attractive.

Variation analysis

Due to the early stage of development, stationary fuel cells (FC) are characterized by a high degree of variation in technological and organizational terms. There are different fuel cell types and system designs along with a wide range of sizes (power output), fuels, operation modes, functions and target customers. Moreover, the organizational structures of the field are not yet established. A large number of actors including start-ups and incumbent firms from related sectors are active in the field. There are frequent entries and exits and the modes of organizational interaction and collaboration are still in flux.

Socio-technical variation

In the case of fuel cells, socio-technical variants can be distinguished along several sub-dimensions such as function, type and size of the fuel cell or major customer segments, cf. Table 1.[10] Each dimension can be sub-divided into a set of discrete values (or value ranges), which can be combined in different ways. In our analyses, we identified four combinations that are assumed to represent the major application contexts for stationary fuel cells in the future, cf. Table 1. If fuel cells are used for uninterruptible power supply, they represent a backup for homeowners or commercial customers in the event of a blackout of the general, grid based electricity supply. In this application, the fuel cell system is in a stand-by mode most of the time and just operates for a few hours once in a while. Particular requirements are high reliability and a short start-up time, while overall efficiency, lifetime of the stack or continuous fuel supply are less important.

In all the other application contexts, however, parameters such as efficiency and generation costs, fuel supply and lifetime are critical because fuel cells typically have to cover long operating times. The units operate in a cogeneration mode, in which they supply power and heat to cover the local demand (micro- and mini-cogeneration), but the technology may also become so cost-efficient that it can be used just for electricity generation in semi-decentralized power plants. In the case of micro- and mini-cogeneration, stationary fuel cells will be adapted to the heat demand of residential buildings or functional buildings (offices, public buildings, hospitals, small enterprises), respectively. Finally, electric utility companies may use stationary fuel cells to generate electricity in small power plants, e.g. for peak load supply.

Table 1. Socio-technical variation: Four major application contexts

	Function	Type	Size	Fuel	Operating mode	Customer segment
Uninterruptible power supply (UPS)	FC provides backup in the case of electricity network outages.	All	Small to medium (1-50 kW)	Hydrogen and natural gas	Power only, short operating times	Private and commercial customers
Micro-cogeneration (µ-CHP)	FC provides decentralized supply of power and heat.	PEMFC, SOFC	Small (1-5 kW)	All (primarily natural gas)	Cogeneration, long operating times	Private and commercial (house owners)
Mini-cogeneration (m-CHP)	FC provides decentralized supply of power and heat.	All	Medium (50-250 kW)	All	Cogeneration, long operating times	Commercial (owners of functional buildings, commercial premises etc.)
Small power plants (SPP)	FC provides semi-decentralized power supply.	All	Large (above 1MW)	All	Power only, long operating times	Commercial (electric utilities)

Whether or to what extent the aforementioned application contexts will become important depends on the development of the technology itself but also on a number of factors that can be related to the innovation system context. A significant decrease in fuel cell system costs, for example, is particularly favourable for large fuel cell plants where costs are a major factor determining adoption. For micro-cogeneration we also found other factors such as lifestyle to be important for customers, while a decreasing reliability of electricity supply is a key factor promoting uninterruptible power supply. Cogeneration is less driven by security of supply than by public support or the acceptance of installers. The list of factors and causalities could be extended further; Table 2 lists a series of influencing factors and how they might affect the different application contexts.

Table 2. Effects of internal and external developments on application contexts

	UPS	μ-CHP	m-CHP	SPP
Internal				
Significant decrease in FC system costs	+	+	++	++
Regime level				
Decreasing security of electricity supply	++	+	+	o
Public support for cogeneration	o	++	+	o
Many installers accept stationary fuel cells	o	++	+	o
Landscape level				
FC becomes a lifestyle element	+	++	+	o
Competing innovations				
Large scale diffusion of solar heating	o	--	-	o
Progress in engine based cogeneration	o	-	--	-
Complementary innovations				
Diffusion of energy services	+	++	++	o

Explanation: ++ strong influence, + medium influence, o no influence, - negative influence, - - very negative influence

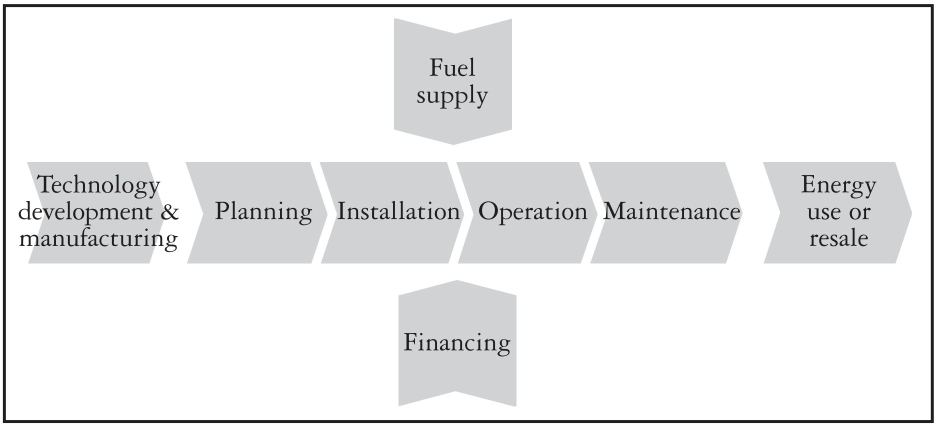
Organizational variation

Here we are interested in the roles different actors or actor groups might play when it comes to the installation and operation[11] of stationary fuel cells. As a first step, we distinguished some generic tasks along the supply chain that need to be fulfilled in order to produce energy from fuel cells. These include planning, installation, operation and system maintenance but also fuel supply, financing, technology development and manufacturing as well as energy use or energy resale (Figure 2). Note that planning and financing are less important for small fuel cells and rather part of other tasks.

As a second step, we differentiated groups of actors such as technology manufacturers, engineering companies, installers, utility companies, financiers and energy consumers. Each actor group has been defined on the basis of the core business of its firms. Actors in each group may fulfil one or several tasks. On this basis, three major organizational variants, so-called role models were identified, which represent particular constellations of actor groups and tasks, cf. Table 3.

In the first model, utility companies offer their customers one-stop energy supply from fuel cells including fuel cell operation and financing. The customers sign a long term contract (e.g. for 10 years) for power and heat supply. In this case, utility companies work closely together with local installers and fuel cell manufacturers. Such a highly integrated model is current practice.

Figure 2. Generic tasks for producing energy with stationary fuel cells



As an alternative, we might also see a future situation in which fuel cells are marketed like heating boilers, i.e. customers ask 'their' local installer to recommend and install a system. They are responsible for financing and operation and they call the installer if there is a need for troubleshooting or maintenance service. Fuel supply in the form of natural gas is organized independently. This model requires a high degree of technological maturity, e.g. few failures and reasonable up-front investments by the customers.

While these two models seem to represent extremes in terms of integration, further combinations or variations are possible. In the third model, for example, newcomers from other sectors (or new firms) work together with local installers and position themselves as energy service providers, which offer decentralized energy supply from fuel cells. As in the heat market model, fuel supply may come from established gas utility companies or from other suppliers (e.g. in the case of hydrogen).

Table 3. Characteristics of major organizational role models

	Manufacture	**Planning**	**Installation**	**Maintenance**	**Operation**	**Financing**	**Fuel supply**	**Energy use**
Utility role model	Manufacturer	Electric or gas utility company, installers as sub-contractors						Customer
Heat market role model	Manufacturer	Engineers / Installers	Installers		Customer		Gas utility company	Customer
Newcomer role model	Manufacturer	Newcomer (energy service provider), possibly installers as sub-contractors					Gas company / others	Customer

Changes within the existing organizational structure and the emergence of new role models depend on several influences that can be related both to the innovation system and its context, see Table 4. Major internal drivers are decreasing investment costs and increasing reliability. Both may work in favour of a model with a low degree of integration because risk outsourcing in the form of contracting will become less important. At the regime level, increasing competition is certainly an incentive for the utility model. The heat market model may be driven by the degree to which a majority of installers accept the novel technology. The influence of competing innovations on role models is less obvious. However, we might expect that the diffusion of solar heating, for example, acts in favour of the heat market model. A very strong diffusion of solar, however, will generally impede the diffusion of fuel cells and slow down technological progress. This again favours contracting based offerings as in the utility or newcomer model. With regard to complementary innovations, finally, a broader diffusion of energy services may positively influence the utility model and the newcomer model.

Table 4. Effects of internal and external developments on role models

	Utility model	Heat market model	Newcomer model
Internal			
Decrease in FC system costs	-	++	-
Increase in FC reliability and lifetime	-	++	-
Regime level			
Strong competition in the electricity or gas sector	++	o	o
Many installers accept stationary fuel cells	o	++	o
Competing innovations			
Diffusion of solar heating	o	+	+
Complementary innovations			
Diffusion of energy services	+	o	++

Explanation: ++ strong influence, + medium influence, o no influence, - negative influence, - - very negative influence

Synthesis (combination)

The discussion of organizational role models has already indicated that there are linkages with socio-technical development options. Some application contexts show a better fit with particular organizational structures than others, e.g. because there are synergies between the established businesses of strategic actors and the new, fuel cell related activities. Cogeneration, for example, is well compatible with the utility or heat market model as the key players of these two organizational variants are already active in similar fields and possess customer contacts as well as the necessary know-how. However, newcomers might also find a profitable niche for medium size fuel cells, which they offer to commercial customers or public entities in combination with energy saving or load management services. In the case of uninterruptible power supply (UPS), newcomers may play an even more important role as the devices can be installed and operated rather independently of infrastructure and know-how in the fields of electricity supply, gas supply and heating. But also electric utilities may discover UPS as a new, promising business area complementing their traditional, grid based power supply. Finally, small fuel cell based power plants may have significant potential synergies with the utility model but not with the other organizational variants. The following table shows where synergies, and thus more likely combinations of the two major dimensions are to be found. Current constellations of application contexts and role models are highlighted.

According to these findings, changes may occur in the two cogeneration application contexts. Micro-CHP fuel cells may very well be offered on the basis of the heat market model instead of the utility model and mini-CHP can be organized in accordance with all three role models. Future changes with regard to UPS and SPP are less likely but, of course, possible.

Table 5. Expected synergies between organizational models and socio-technical variations

	Utility model	Heat market model	Newcomer model
Uninterruptible power supply (UPS)	+	o	++
Micro-cogeneration (µ-CHP)	+	++	o
Mini-cogeneration (m-CHP)	+	+	+
Small power plants (SPP)	++	o	o
Explanation: ++ high, + medium, o little synergies; grey marks: already realized			

Conclusions

In this article we presented some first building blocks of a methodology for the prospective analysis of emerging, radically new technologies. Empirically illustrated by a case study on stationary fuel cells in Germany, we demonstrated how to identify major development options, i.e. socio-technical configurations and constellations in which different actors may work together. We also analyzed potentially promising combinations of these two dimensions.

Theoretically, the approach is based on the conceptual framework of technological innovation systems combined with the key concepts from transition theory. We claim that this foundation is particularly useful for the study of emerging technologies in a specific, but changing context. In fact, we were able to link the assessment of future development options with the degree of variation in the innovation system, with progress in related innovation fields and with the stability or instability of prevailing regimes. This provides the basis for further prospective analyses including the construction of scenarios and potential development paths.

Before the full potential of such an approach can be reaped, however, advances are needed in many different respects. First of all, the link with ‘established’ scenario methods needs to be strengthened in order to clarify, for example, how coherence conditions can be classified and made operational. The writings of Godet (1986) or de Jouvenel (2000) are certainly promising in this respect. Another area of improvement is the conceptualization of influencing factors, i.e. to distinguish more clearly between external and internal parameters and to relate different variables to the key innovation system elements (actors or activities, networks and institutions). Attention must also be focused on developing the methodological parts that are directed to the elaboration of scenarios and development paths. Finally, further empirical work must be carried out. So far, we have applied the presented approach—in slightly different ways—to three innovation fields including stationary fuel cells, 'smart building' (basic information technology to enable a broad range of convenience and security applications in homes, cf. Konrad 2006) and 'biogas' (decentralized energy production on the basis of anaerobic digestion of biomass, cf. Stadelmann 2006). Cross comparisons of these cases as well as complementary studies in other innovation fields can be expected to make fruitful contributions to the development of a methodological toolbox that combines the need for future oriented innovation studies with the merits of the innovation systems framework.

Notes

[1] Conceptual and empirical work was carried out as part of a larger project 'Integrated Microsystems of Supply' (www.mikrosysteme.org) concerned with the dynamics, sustainability and shaping of transformation processes in network-bound infrastructure systems. See Markard (2006a) with regard to the case study on stationary fuel cells. The project was funded by the German Federal Ministry of Education and Research.

[2] See Markard (2006b) for a more encompassing elaboration of this definition.

[3] While we use 'innovation system' as a conceptual notion with specific characteristics (cf. Markard 2006b), 'innovation field' is the broader term for an area in which innovation activities are carried out and which not necessarily fulfils the conditions of an innovation system.

[4] For an encompassing analysis of actor roles see Markard and Truffer (2006a).

[5] The degree of aggregation and simplification basically determines the number of variations taken into account. Our experiences have shown that about 4–6 variations on each dimension are practicable in terms of effort and analytical clarity.

[6] The full version of this study has been published in German (Markard 2006a) and is available at www.mikrosysteme.org.

[7] These figures include all, i.e. stationary, mobile and portable fuel cell innovation activities.

[8] For further information see www.initiative-brennstoffzelle.de or www.bz-buendnis.de.

[9] Policies may come in the form of general, sector specific or even technology specific regulations. Although we might be inclined to assign general policies to the landscape level, sector specific schemes to regimes and specific regulations to innovation systems, this cannot be taken as a general rule.

[10] Note that the sub-dimensions depicted in Table 1 are partly interdependent, i.e. function largely determines fuel cell size and operating mode. We chose this selection to illustrate the different aspects of each application context. A more strict description of applications on the basis of independent dimensions would just include function, type, fuel and customer segment.

[11] We decided to limit the analysis to this upper section of the supply chain but we could also have investigated the manufacturing part in detail.

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