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Creating and shaping innovation systems: Formal networks in the innovation system for stationary fuel cells in Germany

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ABSTRACT

The development and diffusion of novel technologies, e.g. for decentralized energy generation, crucially depends on supportive institutional structures such as R&D programs, specific regulations, technical standards, or positive expectations. Such structures are not given but emerge through the interplay of different kinds of actors. In this paper, we study the role of formal networks in creating supportive structures in the technological innovation system for stationary fuel cells in Germany. Our findings are based on an in-depth study of five selected innovation networks. The analysis shows that the networks were strategically set up to support the creation of a variety of elements including public R&D programs, modules for vocational training, technical guidelines, standardized components, or a positive image of the technology. These elements have been reported to generate positive externalities in the field, e.g. as they help to establish user–supplier linkages in the emerging value chain. We conclude that, from a firm perspective such elements may represent strategically relevant resources made available at the innovation system level. This view opens up a link to the literature of strategic management, thus highlighting the importance of strategic action and cooperation in emerging technological fields.

1. Introduction

The emergence and development of a new technological field is a complex, multi-faceted process shaped by the strategic moves of innovating actors and by institutional structures, which support, guide, and also constrain technology development. (e.g. Garud et al., 2002; Smith, 1997; Van de Ven et al., 1999). Some of these structures exist and develop rather independently of what is going on in the novel field. Larger systems for education and research, financial services, IPR regimes or labor markets are examples here. Other institutional structures, in contrast, co-develop together with the new technology or are intentionally created by actors in the field. Such structures are typically technology-specific and can be regarded as elements of the emerging technological field. Examples include technological standards (Garud et al., 2002), tests to determine the value of a novel technology (Kaplan and Tripsas, 2008; Rao, 1994), technology-specific regulations and funding schemes (Negro and Hekkert, 2008; Walz, 2007) or collective expectations and cognitive frames (Borup et al., 2006; Kaplan and Tripsas, 2008). For emerging technologies, such elements are of major importance: as they stabilize, shape and legitimate the new field, they create positive externalities for innovating actors (e.g. Aldrich and Fiol, 1994; Bergek et al., 2008a, 2008b; Van de Ven et al., 1999).

A crucial point is that these supportive structures are often deliberately created. Different kinds of organizations may even work together and coordinate the strategies through which they shape the field they are operating in (Garud and Karnoe, 2003; Garud et al., 2007; Van de Ven, 1993). In this paper, we take a closer look at how an emerging technological field in the domain of decentralized energy supply was deliberately shaped through the coordinated actions of innovating actors. Our analysis shows that formal innovation networks played a crucial role in creating and shaping supportive institutional structures in the field of stationary fuel cells in Germany. We will argue that in order to foster the development of novel technologies, it is important to follow the strategic moves of the actors in the field (cf. Markard and Truffer, 2008a). As we understand the conditions under which they join forces and establish supportive structures, for example, we can better inform technology-specific support policies.

Our conceptual starting point is the technological innovation systems (TIS) perspective. The TIS concept has received quite some attention in recent years as an analytical framework for the study of emerging technologies (e.g. Carlsson et al., 2002; Edquist, 2005; Jacobsson and Johnson, 2000; Markard and Truffer, 2008b). In the domain of new energy technologies, numerous cases and

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countries have meanwhile been analyzed (Bergek and Jacobsson, 2003; Jacobsson and Johnson, 2000; Jacobsson, 2008; Markard and Truffer, 2008a; Suurs and Hekkert, 2009). The TIS approach highlights both the role of institutional structures and the importance of organizational actors in the emergence of technological innovations. However, how the actors strategically create institutional structures and how this affects the build-up process of TIS has not been analyzed in any detail. In the following, we will analyze how organizations join forces in formal networks, which then create and shape supportive elements at the level of the innovation system.

Formal networks are inter-organizational relationships of firms and other actors whose goals are the achievement common aims. Such networks encompass strategic alliances, working groups of associations, technical committees or project networks. In our empirical study, we focus on a selection of five major formal networks in the field of stationary fuel cells in Germany. Interviews have been conducted to capture in detail the activities that were carried out by the selected networks. Our analysis was guided by the following interrelated questions: What kinds of supportive structures, or system elements, do formal networks shape or create? How do these elements contribute to the functioning of the innovation system and what kinds of benefits do they generate for innovating firms?

The broader conceptual motivation for this analysis is to explore the relationship between the strategic moves of actors and the development of new technological fields. The idea is to conceptually and empirically strengthen the analysis of micro-meso-level linkages in innovation studies (cf. Markard and Truffer, 2008a). Here, we address the issue as to how structures within technological innovation systems are strategically created, a topic that is of key importance to the formulation of policies to support novel technologies (Bergek et al., 2008a, 2008b; Hekkert et al., 2007; Jacobsson and Johnson, 2000).

The paper starts with a theoretical part, in which we elaborate on the conceptual framework our analysis is based upon. This is followed by the Section 2. In Section 4, we introduce our empirical field of study and the networks selected. Sections 5 and 6 present the findings of the empirical analysis. We report on the activities carried out in the selected innovation networks, the system elements created and the effects these elements have. Section 7 concludes.

2. Theoretical background

For the study of emerging technologies, the innovation systems perspective represents a useful framework (e.g. Carlsson et al., 2002; Edquist, 2005). Below, we briefly introduce the technological innovation systems concept and discuss our understanding of formal networks. Based on these steps, we present our analytical framework that links actors, formal networks and elements at the system level.

2.1. Technological innovation systems: basic concept and system functions

A technological innovation system (TIS) can be defined as a 'network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure or set of infrastructures and involved in the generation, diffusion, and utilization of technology' (Carlsson and Stankiewicz, 1991). Actors include firms or firm sub-units, governmental and non-governmental agencies, universities and research institutes with different competencies, resources and strategies. Institutional infrastructures encompass norms, laws, regulations, guidelines, values, culture, cognitive frames, collective expectations, etc. Institutions influence the activities and decisions of the actors, and they enable, but also constrain action. At the same time, actors have some discretion to change institutional structures and the environment they are operating in.

Current research on technological innovation systems has its strength in the analysis of structures and system functions. System functions are understood as key sub-processes that are important for the build-up and functionality of TIS. The functions are very helpful in tracing the performance of TIS and will be used in the subsequent analysis (cf. Section 6.2). Table 1 presents an overview and some of the indicators used to track the different functions.

Table 1
Overview of TIS functions..
Source: Adapted from Bergek et al., 2008a; Hekkert et al., 2007

Function (label)	Definition	Indicators to track the function
Entrepreneurial activities (F1)	Presence of active entrepreneurs as a prime indication of the performance of an innovation system, concrete activities to appropriate basic knowledge, to generate and realize business opportunities	Mapping the number of new entrants, number of diversification activities of incumbent actors, the number of experiments with the new technology
Knowledge development (F2)	Activities that to creation of knowledge through processes of learning e.g. learning by searching, learning by doing	Number of R&D projects, R&D investments or patents in a specific field
Knowledge diffusion through networks (F3)	Activities that lead to exchange of information but also learning by interacting and learning by using in networks	Number of workshops and conferences, network size and intensity
Guidance of the search (F4)	Refers to those activities that positively affect the visibility of wants of actors (users) and that may have an influence on further investments in the technology	Targets set by governments or industries, number of press papers that raise expectations
Market formation (F5)	Involves activities that contribute to the creation of a demand or the provision of protected space for the new technology	Number of niche markets, specific tax regimes, environmental standards
Resource mobilization (F6)	Activities that are related to the allocation of basic inputs such as financial, material or human capital for all other developments in TIS	Detecting by interviews, whether or not inner-core actors perceive resource access as problematic
Creation of legitimacy (F7)	Activities that counteract resistance to change or contribute to taking a new technology for granted	Rise and growth of interest groups and their lobby actions
Development of positive externalities (F8)	Outcomes of investments or of activities that cannot be fully appropriated by the investor, free utilities that increase with number of entrants, emerge through firm co-location in TIS	Search for external economies as resolution of uncertainties, political power, combinatorial opportunities, pooled labor markets, etc.

The analytical focus on system functions, however, runs the risk of losing sight of the important role of actors (Markard and Truffer, 2008a). Positive externalities in innovation systems, for example, are conceptualized as side effects of an accumulation of actors and 'critical mass' (cf. Bergek et al., 2008a; Jacobsson and Bergek, 2004). Similarly, an emergence of specific labor markets, dedicated service providers or knowledge spill-overs is explained by an enlargement of the actor base or co-location effects. In contrast to that, we will argue that the aforementioned system effects do not just emerge as a quasi-natural phenomenon. Instead, they may also be the result of deliberate activities of actors.

In this paper we argue that actors strategically influence system-level elements (cf. Fig. 1). Because they typically cannot achieve this task alone they join forces in formal alliances, or networks (see below).

2.2. Networks in innovation systems: types and roles

The concept of networks plays a major role in the innovation systems perspective (e.g. Carlsson and Stankiewicz, 1991; Chang and Chen, 2004; Edquist, 1997; Jacobsson and Johnson, 2000). Networks of actors facilitate interactive learning (Lundvall, 1992) and the exchange of knowledge and information (Carlsson and Stankiewicz, 1991; Edquist, 1997). In fact, innovation systems have been conceived of as networks of agents, as social systems constituted by actors and, institutions and by the various linkages that connect them (Carlsson and Stankiewicz, 1991; Markard and Truffer, 2008b). In a continuum from loose linkages to dense configurations, different types of actor networks have been distinguished in the literature. Learning networks, for example, link suppliers and users, universities, industry, etc., and constitute important modes for the sharing and transfer of knowledge (Carlsson and Stankiewicz, 1991; Weber, 2002). Political networks, as another example, consist of actors who share certain norms, beliefs and share a political agenda to influence the institutional set up (Bergek et al., 2008b; Weber, 2002).

In a general way, formal and informal networks can be differentiated. Formal networks have been purposefully established for strategic reasons, while informal networks have emerged in a less planned way through the interaction of organizations. Informal networks are sets of ties within the broader social and regional context actors are embedded in (Molina, 1998). They are typically not directed at a specific goal, nor do they have clear boundaries in terms of who belongs to the network and who does not. Formal networks, in contrast, are usually set up in order to solve a specific task and firms or other organizations deliberately enter these arrangements to achieve a common goal. In comparison to informal networks they are equipped with own resources such as a network management, a budget, or a webpage to create visibility for instance.

Above all, the innovation systems perspective stresses the role of informal networks. The linking of actors and the exchange of knowledge and information rather than the execution of specific tasks at the system level are key. However, we expect that formal networks have a more explicit role in TIS and are a means to realize strategies of innovating firms and to influence the build-up process of a system.

2.3. Formal networks: rationale for focus and definition

The analysis in this paper is based on the underlying rationale that firms and other actors strategically create and shape the elements and structures of the technological innovation system they are operating in. We assume that actors often join forces in formal networks to achieve this aim (cf. Fig. 1). However, it might also be the case that some actors have the resources to shape system elements without the help of others. In our view firms join formal networks not only to gain access to the immediate services a network provides (e.g. information exchange), but also to establish or change institutional structures at the level of the innovation system. These system elements, in turn, generate benefits (positive externalities) for the actors in the TIS thus contributing to the system functions (Fig. 1). In the following, we concentrate on formal networks and their role in creating system structures although we acknowledge that they are not the only source of the emergence of system elements.

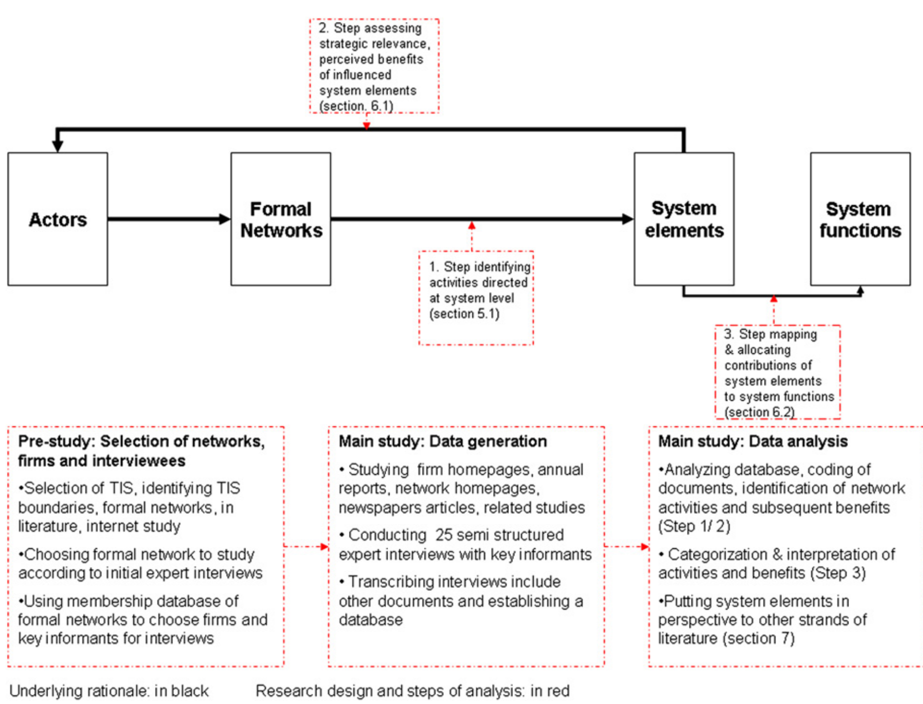

Fig. 1. Analytical framework: underlying rationale and steps of analysis.

Our concept of formal networks is inspired by the literature on strategic management and innovation (Duschek, 2002; Gulati, 1999; Gulati et al., 2000; Ozman, 2009; Sydow, 1992). Networks are an intermediate form of organization between market and hierarchies. They are characterized by the participation of legally independent, but economically dependent organizations that pursue a certain collective aim that determines the area and the length of the co-operation (Duschek, 2002; Sydow, 1992). Formal innovation networks, as a subgroup of organizational networks, will be defined as strategically established inter-organizational relationships of firms and other organizations with clearly identifiable members and a common aim or strategy.

3. Analytical framework and methods

For a fruitful study of the system-level effects of formal networks the research design and a sound analysis were essential. Following our analytical framework shown in Fig. 1, we conducted a pre-study to delineate the TIS and to choose the formal networks and member firms to study. This was followed by the main study in which we interviewed network members and then analyzed and interpreted the collected data.

3.1. Selection of formal networks and interviewees in the pre-study

The first task of the pre-study was to define the boundaries of the innovation system to study. For this purpose we drew on existing studies on stationary fuel cells in Germany and other countries (Brown et al., 2007; Hendry et al., 2008; Markard and Truffer, 2008a; Nygaard, 2008) and also analyzed the broader context including other sectors (e.g. power supply) or complementary innovation systems (e.g. small-scale co-generation). We decided to concentrate on Germany because the country is characterized by a high number of actors and networks in this field (Ruef and Markard, 2010). Stationary fuel cells were chosen in order to reduce the complexity of the study.

Subsequently, we searched the internet and scholarly literature to identify formal networks in the field of fuel cell technology in Germany. The results included about 50 formal networks such as regional innovation networks, industry alliances, project networks, technical committees, or working groups of industry associations. Many of these networks were deselected because they had a very local or regional character. Other networks had just existed temporarily and were not active any more. From the remainder of about a dozen networks we finally selected five for an in-depth analysis. Three networks were chosen on the basis of three expert interviews. All experts identified the IBZ fuel cell initiative, its major project network Callux and the VDMA[1] fuel cell working group as key networks in the field of stationary fuel cells in Germany. To capture the variety of the network population in the TIS, we additionally included the Fuel Cell and Hydrogen Network North Rhine Westphalia (NRW) as an important regional network and the VDI[2] committee 'fuel cells in the household energy supply' as an example of a technical committee.

3.2. Data sources and data analysis in the main study

In the second part of the study, interviews were conducted with representatives of organizations who were members of the selected networks. Interviewees were chosen according to their commitment and duties in the networks (e.g. network management, position in advisory board, etc.). For information on member organizations and the role of different people in the networks, we were able to use membership databases and the web-pages of the networks.

For the preparation of each interview, firm homepages, annual reports, newsletters, network homepages, and newspaper articles were examined. Semi-structured expert interviews were conducted. Every interview included questions about R&D activities and firm strategies, the organization and activities of a particular network, the perceived benefits from being part of the network and the impacts of network activities at the system level. Twenty-five interviews were carried out (1.5 h on average), and another fifteen interviews (same firms and informants) could be used as additional sources of information (triangulation Yin, 1994) from a related project. Interviews were fully transcribed and consolidated with the other documents (e.g. annual reports, newsletter, firm and network homepages, press releases, etc.) in a database.

In the subsequent text analysis we were assigning labels to text units (Miles and Huberman, 1994; Strauss and Corbin, 1996). In the focus was the identification of network activities directed at the system level and the coding of quotes stating the strategic relevance and the perceived benefits of theses network activities (steps 1 and 2 in Fig. 1). Internal network activities that result in exclusive services for network members (e.g. access to information, reduction of expenditure through joint PR activities) were not included. At the end of this analytical step the identified activities were classified and grouped in empirically induced categories of key activities (cf. Section 5.1).

In the final, more interpretational step (data analyses, Fig. 1), the coded activities were used to identify system elements that they created or shaped. This was conducted in two different ways: First, we identified directly created elements of the networks (standards, guidelines were here examples). Second, we also included system elements that have been partly shaped and influenced by the network activities (e.g. positive image of the technology). To control this interpretational step, we also looked at what the interviewees said about the benefits of the network activities. Subsequently, identified elements that were reported to produce important externalities in the TIS were labeled as system elements. In addition, the contributions of the influenced elements at the system level were mapped and allocated to the TIS functions (cf. Section 2). Finally, we put the identified elements in perspective and related them to concepts in the field of strategic management (cf. Section 7).

4. Fuel cell innovation system and major networks in Germany

The fuel cell is a technology in an early state of development. Fuel cells are installed in pilot projects and field tests but not yet produced in greater numbers (Adamson, 2005; Adamson and Crawley, 2006). Still, the contours of a technological innovation system are already visible.

4.1. Technological core, actor groups, and TIS linkages

Fuel cell technology is based on an electro-chemical process in which hydrogen or natural gas is converted into electricity and heat (Carrette et al., 2001). Today, fuel cells are used for different applications: in cars, forklifts, boats and buses (mobile fuel cells), in electronic devices (portable fuel cells) and for the energy supply of buildings (stationary fuel cells). Our analysis will concentrate on the latter domain, in which we see large-scale

[1] The VDMA (German Engineering Federation) is one of the key association service providers and offers the largest engineering industry network in Europe.

[2] The VDI (Association of German Engineers) promotes the advancement of technologies and represents the interests of engineers and of engineering businesses in Germany.

applications (e.g. for hospitals, schools, or office buildings) as well as small-scale systems for single- or two-family homes. Both are based on co-generation, i.e. the combined generation of heat and power (CHP). However, the networks we will study are primarily concerned with small residential fuel cell-based heating systems.

Fuel cell-based heating systems consist of different sub-units including the fuel cell itself, the fuel supply system and the energy management system. These parts require different competences and are manufactured by different firms from different industries. The fuel cell technology draws on a broad knowledge base; various actors have to coordinate their R&D activities in the emergent value chain. On a general level, material- and component suppliers, manufacturers, energy suppliers as well as service providers and intermediary organizations can be differentiated (cf. Fig. 2).

Material suppliers provide high-tech components that have to fulfill particular requirements (e.g. heat resistance) in fuel cell applications. Component suppliers combine these core components to produce sub-units such as the fuel cell stack or provide Balance of Plant (BOP) components (e.g. valves and pumps). Manufacturers further downstream in the value chain design and optimize fuel cell heating devices as they integrate the different components and sub-systems into the end product.

Energy suppliers are currently the major users of fuel cell heating systems although they plan to provide services to end-users (e.g. landlords of one- and two-family homes) in the future. They order pilot plants to conduct field tests to develop and test new business models (contracting) and to gain experience with virtual power plants in which large numbers of fuel cells are connected through smart energy grids.

Upstream service providers include suppliers of test equipment and of automated machinery for fuel cell manufacturing. Downstream service providers (e.g. craftsmen, architects) are responsible for the planning, installation and maintenance of fuel cells. Business service providers and intermediary organizations, finally, include national and regional authorities, banks, research institutes, associations and standardization institutes. They provide services along the whole value chain including R&D support, financial services or networking, information exchange and coordination support between various parties (brokerage).

The actors mentioned above play a key role through their activities in existing sectors and/or other emerging fields and, thus, interlink the TIS on stationary fuel cells (Markard and Truffer, 2008a). These linkages are important for the collaborations we observe in the formal networks. Some major players (manufacturers) in the German boiler industry, for example, actively participate in the TIS for stationary fuel cells. With their background in conventional heating systems, these firms contribute to the formulation of technical norms and performance specifications and use their established distribution channels (e.g. close contacts to local craftsmen). In a similar vein, the TIS is also linked to the electricity- and gas supply sector, as most fuel cell producers closely cooperate with energy suppliers in order to commonly develop standards for grid connection and remote control. In this regard, fuel cells face similar challenges (e.g. grid connection, installation and maintenance, qualification and training of craftsmen) as other decentralized co-generation technologies. Players from the boiler industry as well as energy suppliers are also active in micro co-generation, which is why there is some overlap between the different technological fields. A similar overlap exists between the innovation systems of stationary, mobile, and portable fuel cells.

4.2. A brief history of the German TIS of stationary fuel cells

Industrial R&D activities in the field of fuel cells have a long, silent history in Germany. In the 1990s, the technology saw some progress and received public attention — primarily in the TIS of mobile fuel cells stimulated by the vision of fuel cell cars. The innovation activities in the field of mobile fuel cells together with the liberalization of the electricity sector in 1998, also generated a larger interest in stationary fuel cells (Markard and Truffer, 2006). Originally, Sulzer-Hexis was the only company active in stationary fuel cells, but from 1997 onwards, R&D activities for fuel cell heating systems were started by many of the established firms in the German boiler industry (e.g. Vaillant, Viessmann, and Baxi Innotech). Field tests in cooperation with major electricity and gas suppliers were initiated.

During that time the technology received much public attention. Associations (e.g. VDI and VDMA) launched fuel cell working groups and conferences. Manufacturers developed new generations of fuel cell systems and announced a looming market launch. Optimistic expectations about the commercialization prospects and the potentials of stationary fuel cells led to a hype in 2000/2001 and subsequent disappointment (Ruef and Markard, 2010). This was accompanied by a cut back in innovation activities and the exit of some firms between 2002 and 2005.

Despite this backslash the hype induced various institutionalization processes and also shaped public funding schemes. In 2000 and 2001, Germany launched a special program for residential fuel cell power plants as well as the Zukunfts-Investitions-Programm (ZIP), from which more than half of the funds for fuel cells (about 60 Mio. Euro for 3 years) went into stationary applications (Ruef and Markard, 2010). Networks were set up,

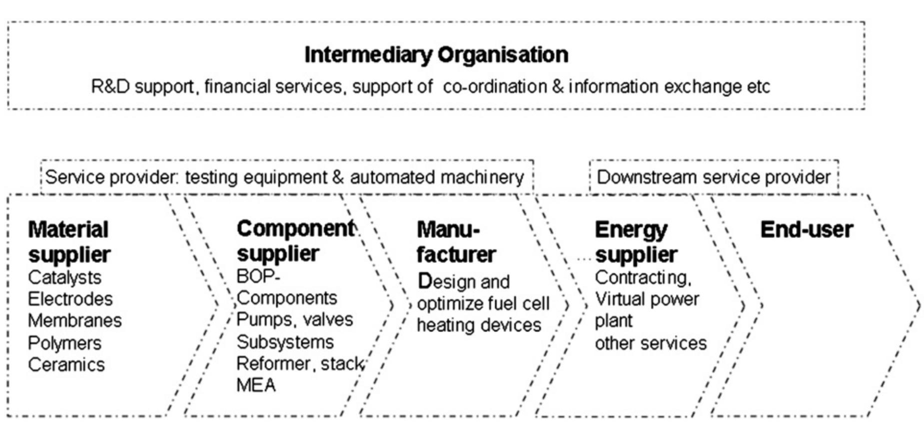

Fig. 2. Outline of fuel cell value chain for stationary applications (the presented value chain is based on previous studies (Nygaard, 2008) and was adapted according to the results of this study. Note that the fuel cell value chain is currently emerging, and the typical actor roles, sub-markets and business models are still undecided).

Table 2
Profile of the formal networks in the study.
Source: interviews and homepages of networks.

	VDMA fuel cell working group	IBZ fuel cell initiative	Callux	VDI fuel cell technical committee	Fuel cell and hydrogen network NRW
Founder/year of foundation	Association 2003	Industry firms 2001	Industry firms 2008	Association 1997	Public authorities 2000
Number of members	Around 55	12	9	18	Around 380
Technical focus	Stationary, mobile, portable fuel cells	Stationary fuel cells	Stationary fuel cells	Micro CHP (Stirling engines, internal combustion engines, fuel cells)	Hydrogen, stationary, mobile, portable fuel cells
Main actor groups	Materials and component suppliers, manufacturers, research institutes, service providers	Manufacturers, energy suppliers, intermediary organizations	Manufacturers, energy suppliers	Energy suppliers, manufacturers, research institutes	Materials and component suppliers, manufacturers, research institutes, service providers
Network mission	Development of fuel cell industry, industry political interest group, industry network for establishment and optimization of fuel cell value chain and cost reduction of fuel cell systems	Support the introduction of stationary fuel cells based on a 'careful preparation, and at the right time, using the right technology'	Launch of gas-driven fuel cell heating appliance to be prepared and support further improvements to ensure marketable products	Supporting market formation for fuel cells and micro-CHP technologies	Positioning of North Rhine Westphalia as a internationally recognized hub for hydrogen and fuel cell technology
Network label	Political network	Strategic alliance	Project network	Technical committee	Regional network

e.g. to link industry and federal ministries in the implementation of the ZIP program (e.g. BERTA and Hybert network), to actively influence the public expectations and communication on stationary fuel cells (IBZ fuel cell initiative) as well as to support regional initiatives (all federal states).

The various institutionalization and network-building processes caused confusion among fuel cell actors and finally resulted in a process of network consolidation. In the following years, the VDMA fuel cell working group and the IBZ fuel cell initiative became influential networks in the field. In 2004, they co-operated through the Fuel cell Alliance Germany to mobilize further financial support by policy-makers. Both networks and other key actors were also active in the Strategy Council Hydrogen and Fuel Cells to prepare the content of a joint national strategy (e.g. National Development Plan, NEP), which finally led to the foundation of a public private partnership and the launch of a National Innovation Program (NIP) Hydrogen and Fuel Cell Technology in 2008.

The NIP is an integrated support program in which research and development and demonstration are closely interlinked, and the federal government, science and industry have pledged support for the development of a German fuel cell industry with €1.4 billion until 2016 (Bonhoff, 2009; Garche et al., 2009). An intermediary organization, the National Organization for Fuel Cells and Hydrogen (NOW GmbH) was also founded to organize the implementation of the NIP.[3] As a result, the various activities in the field were integrated into a coherent national strategy. For example, Callux, a joint field test and lighthouse project of IBZ members undertaken to test 800 fuel cell systems, was initiated and supported by the NIP program in 2008.

The development underlines the importance of formal networks and the strategic implementation of institutional structures such as the NIP program. Key actors came together to actively create and shape processes and elements at the system level. In the following, we take a closer look at the formal networks that played a crucial role in this regard.

4.3. *Characteristics and positions of the innovation networks selected*

Five networks were selected for an in-depth analysis. Table 2 presents some basic features of these networks such as size, types of members, or network mission.

The networks in our sample were founded by existing engineering associations (VDMA and VDI), by firms interested in stationary fuel cell technology (gas suppliers and fuel cell manufacturers) and by a regional authority, the German Bundesland NRW. Network size varies considerably. The smaller networks have 9–18 member firms, while the VDMA fuel cell working group has more than 50 member firms and the NRW network even includes several hundred members.

In the VDMA component suppliers, manufacturers and research institutes of all fuel cell innovation systems (stationary, mobile, and portable) are organized to conduct lobbying activities and coordinate the value chain. The IBZ fuel cell initiative is a network of major energy suppliers and manufacturers to support market creation, product development and grid integration of stationary fuel cell systems. It is closely linked to the Callux project network responsible for coordinating field tests carried out by IBZ member firms. The VDI technical committee on fuel cells develops technical guidelines. Here, mid- to downstream actors such as manufacturers and energy suppliers come together. The fuel cell and hydrogen network NRW finally is a regional network at the nexus of mobile, stationary and portable fuel cell applications. Similar to that of VDMA, it is a forum in which upstream actors such as material and component suppliers meet.

[3] The foundation of the NIP changed existing network structures (e.g. Strategy Council Hydrogen and Fuel Cells) and established new ones such as the NOW advisory board in which delegates of federal ministries and industry (e.g. networks such as VDMA and IBZ) supervise the activities of the NOW GmbH.

Here, the networks goals are more focused on the organization and support of regional industry development.

The comparison shows that although the five networks are very different, they all have the goal of actively contributing – in one way or another – to the development of the broader technological field (and not just to serve the immediate interests of their members). However, goals and mission statements might well deviate from what the networks actually do, which is why we now take a closer look at the actual activities in the networks.

5. Activities of the selected networks and influenced system elements

From the basic analysis of the innovation system, we note that the selected networks play an important role in the development of stationary fuel cells in Germany. In general, networks can be expected to provide immediate benefits for those who are network members. Some network activities, however, aim beyond the circle of members as they influence broader structures at the innovation system level.

5.1. Key network activities directed at the system level

In the following we report on those network activities that create externalities as they deliberately reach beyond the community of network members. To describe our empirical material in a systematic way, we distinguish five types of activities: information exchange and knowledge creation, knowledge diffusion, marketing and communication, lobbying and structuring of the emerging field (cf. Table 3). Note that these types were derived solely from our empirical material although some notions are similar to the system functions (cf. Section 2).[4]

Information exchange and knowledge creation is at the core of most networks. These activities are mostly relevant to network members, but they can also provide benefits for non-members. In the VDMA network, for example, fuel cell manufacturers get into contact with material- and component suppliers, and they use the network to exchange specifications of products to define and optimize interfaces between components of fuel cell systems. As a consequence, integrators can better understand the problems of the suppliers and vice versa. It is also seen that major cost drivers of the final end product are identified as firms with different perspectives work together. While the VDMA facilitates knowledge integration in the upper parts of the value chain, IBZ and Callux members coordinate information exchange downstream: manufacturers and their customers, the energy suppliers, define product specifications and share experiences from field tests. Furthermore, joint technical solutions are developed, e.g., on the desulphurization of natural gas or for data exchange among fuel cell systems. These kinds of knowledge creation activities are relevant at the TIS level because the knowledge is also made available for firms that are not part of the network, e.g., through guidelines, software tools, technological specifications or standardized products.

Knowledge diffusion is also an important network activity. Our analysis shows several examples of how the five networks actively disseminate knowledge to a broad range of actors, i.e. beyond network members. One example is the preparation of courses and vocational training modules for downstream service providers, which is an activity of the Callux network. Network members have specified the content of these modules and subsequently employed academic experts to organize a network for the implementation and diffusion of vocational training. The VDI network again also contributes to the training of service providers such as craftsmen and architects through the publication of guidelines, e.g. on the use of reference load profiles. These reference load profiles have been utilized in a software tool for the planning and dimensioning of small co-generation devices. This simulation software, as an attachment of a guideline, will be used by architects to compare the different technologies energetically.

Marketing and communication activities target the broader public and diffuse layman knowledge, e.g. as they report about recent advances in the field. The general idea is to create a broader societal interest and contribute to shaping a positive image of the new technology. Activities in communication and marketing are conducted by a smaller number of formal networks. Within the IBZ and the Callux network, information materials such as info-CDs, leaflets, marketing movies as well as the content for homepages and press releases have been jointly produced by members. Subsequently, a PR agency was mandated to operate an info-hotline and to organize a professional campaign to publicize the IBZ initiative and the Callux field tests. Through further activities such as joint booths at major fuel cell fairs or press conferences, the IBZ info-material has been distributed to a broader audience.

Lobbying is a main activity of the IBZ and the VDMA network. As an influential industry association, the VDMA has set up and financed a network management and organized a political interest group for the emergent fuel cell industry. Due to the professional support of the VDMA management, the network successfully established an advocacy coalition (Jacobsson and Lauber, 2006): the Fuel Cell Alliance Germany. Furthermore, the VDMA network contributed to the development of the National Innovation Program (NIP) and the formulation of the National Development Plan (NEP). VDMA members today hold three out of 18 positions in the NOW advisory board and are therefore directly involved in the implementation process of the NIP. In addition, the IBZ has positioned itself as the competence center for stationary applications in Germany. IBZ is a key player in NIP and has influenced the decision that one third of the NIP investments will be reserved for stationary applications. Furthermore, IBZ members closely worked on the formulation of R&D priorities for stationary applications in the NEP.

Structuring of the field, finally, subsumes activities that bring previously unconnected actors together, specify inter-organizational interfaces, facilitate exchange and, thus, help establish market structures. It is an important activity in the VDMA and in the NRW regional network. The VDMA network, as the leading industry network, has taken the initiative to initiate a dialog between different kinds of suppliers and system-integrators. Subsequently, members have been engaged in the definition of joint problems in specific working groups and the exchange of specifications and information. As a result, firms find it easier to organize further exchange on a bilateral basis. In addition, firms are currently harmonizing their components and systems to implement a Japanese connector technique and facilitate the integration of sub-systems. Another example is the set-up of the small-scale devices program (KGP) through the VDMA. IBZ and VDMA members evaluate KGP project proposals and in the course of funded projects suppliers adapt standard components or conduct workshops with manufacturers to define component specifications, for example. The NRW network finally, integrates new firms into the field. Network management actively invites firms from related industry sectors to participate, and it also brings potential partners together.

The general pattern that emerges from the analysis is that all of the selected networks conduct or coordinate activities that support the development of the innovation system for stationary

[4] Our interpretation of these similarities would be that some network activities make quite an immediate contribution to system performance, which again is reflected in the system functions.

Table 3
Activities of the networks with expected system-level effects.
Source: interviews.

Main types of activities	VDMA fuel cell working group	IBZ fuel cell initiative	Callux project network	VDI fuel cell technical committee	Fuel cell and hydrogen network NRW
Information exchange and knowledge creation	• Exchange specifications of components and fuel cell systems • Identify major cost drivers in step towards mass production • Adapt fuel cell systems and components, reduce complexity of sub-product interfaces	• Optimize application of fuel cell systems • Stabilize manufacturers after the fuel cell hype • Develop common standards and methods for performance measurement	• Organize and execute joint lighthouse house project • Use of experiences of field tests to improve prototypes • Develop interface for data transfer (Callux box) • Develop technical solutions for desulphurisation of natural gas (associated NIP project) • Specify content for vocational training	• Integrate knowledge and experiences for drafting service contracts • Specify, produce and use of reference load profiles of German households • Specify, produce and use simulation software for testing and dimensioning of micro-CHP	• Support the networking and information exchange of firms
Knowledge diffusion	• Make available technological specifications to existing and new members • Agree on performance classes and diffuse common standards	• Provide specific info-CDs, info materials for service providers • Develop and diffuse technological norms and standards	• Employ experts to organize module for vocational training • Develop a network for the vocational training on fuel cells in Germany • Develop and diffuse educational material for module for vocational training of service providers • Train utilities and service providers in the field tests modules	• Produce and publish technological guidelines about drafting service contracts and use reference load profiles • Produce guidelines with attached planning tool for service providers (simulation software for dimensioning of micro-CHP)	• Conduct seminars and conventions and other services • Provide database with members and fuel cell products • Offer advice for new entrepreneurs in the field
Marketing and Communication		• Employ a PR agency • Develop and distribute fuel cell info-CDs • Run IBZ webpage and info-hotline • Provide booths at fuel cell fares • Coordinate and produce content for joint press releases	• Employ a PR agency • Run Callux webpage and info-hotline • Produce Callux fuel cell field test movie • Coordinate and produce content for joint press releases about field tests		• Provide joint booths at international fares • Organize and support projects and events to increase visibility of fuel cell technology in NRW
Lobbying	• Establish interest group • Initiate Fuel Cell Alliance Germany and arrange meetings with politicians • Inform politicians about potential and activities in emergent fuel cell industry • Formulate, adjust content of NEP • Lobby for financial support of small-scale device program (KGP) • Influence implementation of NIP and adaptation of NEP through NOW advisory board	• Organizing an interest group for stationary fuel cell applications • Support establishment Fuel Cell Alliance Germany • Inform politicians about potential of stationary application • Achieve joint R&D aims in the stationary part of NEP • Influence implementation of NIP and adaptation of NEP through NOW advisory board			
Structuring of emerging field	• Motivate and integrate newcomers • Initiate exchange and facilitate pre-	• Develop technolo-gical norms and standards • Evaluate project			• Motivate (entry of newcomers), integrate and support newcomers

Table 3 (*continued*)

Main types of activities	VDMA fuel cell working group	IBZ fuel cell initiative	Callux project network	VDI fuel cell technical committee	Fuel cell and hydrogen network NRW
	selection of partner • Initiate harmonizing of specifications, facilitate introduction of common standards • Organize and supervise small-scale device program (KGP)	proposals in small-scale device program (KGP)			• Bring interested parties together (brokerage) • Coordinate regional projects

fuel cells as a whole. More specifically, all networks pursue knowledge creation and diffusion activities, while they have different foci in the other three activity dimensions. VDMA and IBZ, for example, are very active in lobbying, while marketing activities are primarily driven by the IBZ and the related Callux project network. The different foci reflect the different goals of the networks and show that there is a certain degree of coordination (division of labor) among the networks.

In the next section, we add a somewhat different perspective as we ask what has changed at the level of the innovation system due to the networks' influence. We will see that the networks have created new elements at the system level and also shaped or modified existing structures.

5.2. System-level elements created and shaped by the selected networks

Due to the influence of the five networks, new structures emerged in the innovation system for stationary fuel cells. These include support programs, technical guidelines, standardized technical components or training modules, for example. Fig. 3 shows these new system elements. Those that were under t rather direct control (black solid arrows) of our networks are colored in green, whereas those that were influenced to a finite extent (gray arrows) are colored in light green. The five networks are represented by blue ovals. The picture also shows that other actors, i.e. not just network members, played a role in shaping the different system elements. Some of these were identified by name in the interviews (blank circles): others were just referred to in a general way (short dotted arrows). Furthermore, we distinguish different kinds of system elements including institutional structures (sickles), actors or actor groups (circles), and artifacts (squares).

The KGP program, a novel R&D support program for small-scale auxiliary devices, is one example of a new institutional structure at the innovation system level. The program was initiated and lobbied for by the VDMA network and is now operated by both VDMA and IBZ with the support of two research centers. VDMA and IBZ contribute with their knowledge and organizational competencies, while financial support is provided by the Federal Ministry of Economics and Technology.

Another new element is the vocational training module for service providers. It was initiated by the Callux project network and is currently managed by a consortium of institutes for vocational training.

Two networks (VDMA and IBZ) also contributed to the creation of a new formal network, the NOW advisory board. Here, government

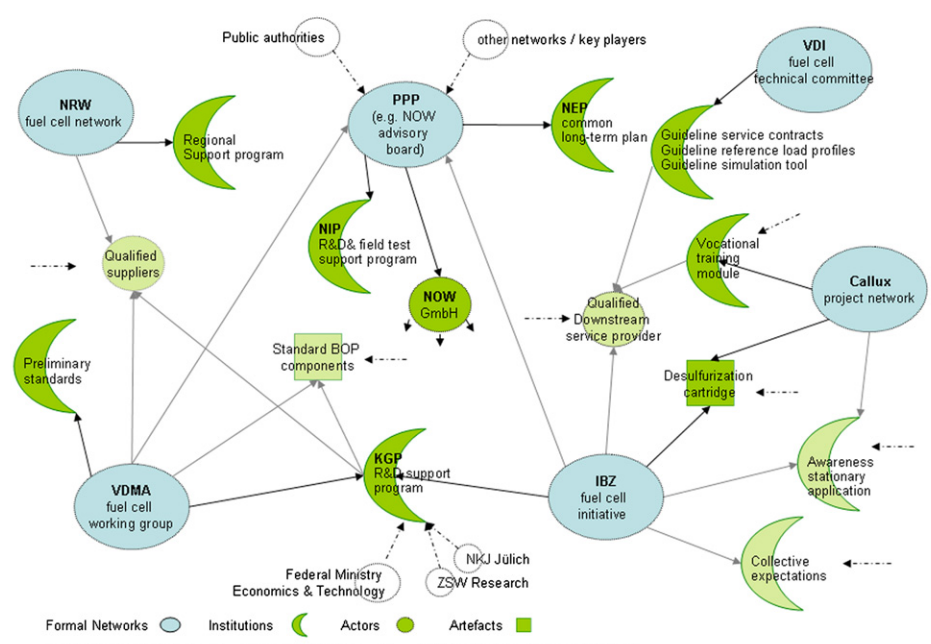

Fig. 3. Selected formal networks of the stationary fuel cell TIS in Germany and their role in creating new system-level elements (for interpretation of the references to color in this figure, the reader is referred to the web version of this article).

officials and representatives of the German fuel cell industry meet regularly to decide on the strategic orientation of the NIP. In a similar vein, the NOW GmbH, an intermediary organization that manages the NIP program, was established. The set-up of these different structures (advisory board, NOW GmbH, NIP, and NEP) was the outcome of a successful negotiation and coordination process of different networks and public authorities. VDMA and IBZ played a crucial role in this process but other networks, e.g. from the automobile industry, were involved as well.

As a final example, we want to highlight that some networks are also involved in creating awareness about the advantages of stationary fuel cells and shaping technology-specific collective expectations. When the hype around fuel cells and the subsequent disappointment (Ruef and Markard, 2010) threatened to negatively affect the image of fuel cell technology, the IBZ started to regularly inform the public about the advantages of the novel technology without exaggerating its prospects. The idea was to highlight the relative importance of stationary fuel cells, which often received less media coverage than mobile fuels. The Callux network also played a role in this regard. Such influences on public awareness and collective expectations, however, are difficult to track, and we cannot assess how the impact of IBZ and Callux compares with the influences other actors exerted through their corporate communication, for example.

While *new* structures and elements were the focus of this part of the analysis, we also observed that networks played a role in changing *existing* structures. An example is the vocational training modules that qualify specific actors in the TIS and thus change the existing competence base. The aforementioned collective expectations are another example as they are continuously shaped and re-formulated. Networks, in other words, do not just *create* novel system elements but also *change or stabilize* existing structures. As a matter of fact, we may also expect that networks deliberately break up or remove specific institutional structures, although this was not observed in our case.

Finally, the analysis revealed that networks do not work independently. On the contrary, some of the activities were strategically coordinated between networks (e.g. KGP and NIP). It was also reported that networks coordinated their activities in different ways. In some cases, they just joined forces, e.g. to obtain more influence at the political level, while in other cases they used complementary resources as they divided a common task according to the different competencies.

6. Assessing the strategic relevance and the system-level contributions of system elements

We have shown that the selected networks affected various elements in the innovation system. In this final part of the analysis, we address the issue of why they have done so and how the observed changes were of broader relevance, as they generate benefits and positive externalities at the TIS level.

6.1. Strategic relevance of the created and shaped system elements

The structural changes described above have been strategically relevant in the processes of system formation for the firms that were involved as network members. To illustrate which kinds of benefits the novel system elements provide and why firms co-operated in formal networks to create them, we use statements from the interviews.

Different actors support the TIS build-up process through networks. Energy suppliers conduct activities to stabilize and support the manufacturers; to influence collective expectations; and finally to assign roles to craftsmen and architects. Fuel cells, virtual power plants, and contracting models are central elements of the business strategy of an important energy supplier in the field. Due to its vision of the future of the energy supply sector, the firm founded networks for strategic reasons:

> Product manager of an energy supplier: During that time [after the hype], we have tried to stabilize the manufacturers as well the energy suppliers through the IBZ. During that time we have founded the regional initiative, then the Fuel Cell Alliance Germany from which finally also the NOW was initiated, as well as the NIP. Accordingly, we have tried in this way to arrange a 'bed' in which the fuel cell can lie down, framework conditions, which support the development of R&D and which also signal the manufacturer: attention here is a market waiting, You just have to accomplish the technology.

Critical for the realization of the business strategies of committed energy suppliers are, therefore, the innovation activities of the manufacturers. After the hype, for instance, there was the risk that the manufacturer ceased its R&D activities and, as a result, the energy supplier had to intervene within the IBZ fuel cell initiative:

> Project manager of an energy supplier: 'Without the IBZ all larger developers had ceased their work after [the breakdown of] the hype in 2002 [...] I think the IBZ signaled that utility companies have a considerable interest in acquiring this technology and I think this also exerted some pressure on the manufacturers of [fuel cell] heating systems to keep on developing the technology.'

The last quotation indicates that the hype and the subsequent collective expectations are important system elements. Positive collective expectations are especially important in young technological fields characterized by an institutional vacuum and low legitimation (Aldrich and Fiol, 1994). They positively affect access to financial resources or broader political support. In addition, strong signals are sent to potential R&D partners, for example, thus mobilizing additional investments. In other words, collective expectations have to be controlled to prevent disappointments and to encourage the innovation activities of suppliers in the field. That is why energy suppliers and manufacturers also became active here:

> Product manager of a manufacturer: The fuel cell initiative was strategically founded in order to create a neutral communication platform and to get away from a person-driven company communication, as we had conducted before. [...] But for mitigating the hype we gathered all at the roundtable and said, before our child that had fallen into the well drowns completely, how can we construct the ladder, which helps it to come out. And the ladder is the fuel cell initiative. And the communication of the fuel cell initiative has been moderate from the beginning. [...] We have then embedded the firm communication within the fuel cell initiative communication. Thus, it was not necessary anymore, that we ballyhoo in competition, each opposing the competitor, outbid each other with hype slogans; but we said, let us create this platform and become more moderate, in order to get it going according to a new timing, maybe in 2010. [...] Remaining silent was not an option either. Then we had fallen even deeper. Now we pass the [expatiation] valley not at its deepest point, because we have a common communication strategy.'

For the business strategies of energy suppliers, the integration and qualification of service providers is also a strategic issue. It is expected that energy suppliers that co-operate at an early stage with craftsmen and architects obtain an advantage due to the developed reputation and routines. However, what is more important here is that actors co-operated to set up the Callux vocational training module, for instance, to better define the roles and tasks of different service providers in addition to reducing their resistance to change. The various technical guidelines developed by the VDI network have a similar effect, as they establish common quality standards related to planning, installation and grid integration:

> Project manager of an energy supplier: 'For craftsmen and market partners we have educational programs[…] Craftsmen need to be competent in order to perform perfectly, to give the correct advice to their customers. This is why they need to be educated[…] Otherwise, the technology gets a bad image, like heat pumps in the 70s which were installed incorrectly because craftsmen could not handle the technology.'
>
> Project manager of a research institute: 'The developers [manufacturers] saw clearly that they have to provide tools [technical guidelines] for craftsmen so that they [craftsmen] know what they are doing and that also the developer knows what the craftsman does, to have control here.'

Manufacturers are currently struggling to optimize the value chain, to meet performance standards and to reach an acceptable price of stationary fuel cells. Therefore, component suppliers are supporting manufacturers and initiated the small-scale device program KGP (within the VDMA network) to mobilize and stimulate the commitment of BOP suppliers in the field of fuel cells. As the product manager of a major component supplier puts it:

> It was important to keep the suppliers of specific BOP components interested [in the technology]. The KGP facilitates small projects, small steps [not covered by the existing programs] … If you want to modify a standard valve, they [suppliers] do not spend money on this; it does not fit into their development processes. But with the KGP, you can conjointly work on such small things. [it also supports] self-marketing of the fuel cell […] You can show that there is a broader interest, that it receives attention at the national level.

Programs like the KGP can build bridges, as they provide financial support and stimulate co-operations between manufacturers and component suppliers in a market that is still immature. Such co-operation-contributes to qualifying suppliers and the diffusion of knowledge, which is particularly important for newcomers in the field. They can now develop fuel cell specific competencies or optimize fuel cell components in joint KGP-financed projects with more experienced actors (e.g. manufacturers).

Furthermore, the KGP supports the coordination of actors and standardization as the development of (standard) components is supervised by IBZ and VDMA. A larger picture behind this is that specific R&D support programs are very helpful for creation of a value chain and the development of business models. NIP and KGP are tailored to support cooperation among firms from different industries while the value chain is coordinated:

> Manager of major component supplier '[With the NIP] R&D projects have become more flexible, you don't need umpteen firms, three universities and five different countries. This is important; now firms can develop and test partnerships under fixed conditions [and get financial support] This helps tremendously in developing the technology but also for value chains […] If you take a look at how networks have emerged, you see that many co-operative agreements began with such a project.'

In addition, the interviews have revealed that support programs such as KGP and NIP are important for legitimizing fuel cell activities and signaling market potential:

> Manager of an intermediary organization 'We have to stop the slow deterioration of the industrial core [in the field] […] The money must be circulated, for research activities […] Suppliers have to see, yes, this is serious, we have this market [opportunity] and it is deliberately pushed; there is a broader interest. - This is what you build a management decision on.'

Above all, the quotations exemplify that formal networks have been used to create and shape system elements for strategic reasons. However, most strategic decisions have been driven by the goal of establishing the technological field and not primarily of serving particular firm interests (e.g. establishing a firm standard at system level). Even more, some elements have been used as a means to efficiently shape other system elements. KGP, NIP, the training module and the VDI guidelines, for instance, were among others created to attract further industry firms and to qualify suppliers and craftsmen (cf. Fig. 3). Furthermore, it was reported that the system elements provide positive externalities such as public financial support, the deliberate diffusion of knowledge or the creation of legitimacy. These contributions at the system level can be allocated to the system functions and indicate how important the identified system elements for TIS development are.

6.2. System level contributions of the identified elements

In Section 6.1, we have illustrated some of the effects the networks generated as they started to actively shape the innovation system on stationary fuel cells. In Fig. 3, we have summarized and generalized which different types of system-level elements the networks created or shaped. These include formal institutional structures (support programs, standards, and guidelines) but also informal, cognitive structures (collective expectations, awareness and image of technology). Furthermore, artifacts were developed and new organizations and even new networks were created. For each element, we also listed which system functions were affected. This assessment is based on a systematic analysis of interview transcripts and on indications in the statements that point to the key criteria of each function (cf. Table 1).

The general pattern that emerges from the analysis above is that most of the system elements contribute to the system functions "knowledge diffusion", "guidance of search" and "creation of legitimacy" while "entrepreneurial activities", knowledge development and market formation are less affected. However, our study also revealed system-level effects that are not covered by the existing functions.

Most of the identified elements support coordination and value chain creation in the field. The KGP support program, the Callux vocational training module in addition to the activities of the VDMA in integrating newcomer and introducing common technological standards reveal that the integration of suppliers, as well as the assignment of specific tasks in the value chain are processes which are actively coordinated and pushed by formal networks. In addition, the value chain creation is accomplished by the work of the NOW GmbH. The overall coordination of the value chain and of the fuel cell field in general could be, therefore, a key process in the innovation system that has not been mapped with system functions in any detail (Table 4).

The list of supportive system elements presented above must be interpreted in light of the design of our study. We only analyzed a subset of the networks in the field of stationary fuel cells and, therefore, we might have missed system elements

Table 4
Different types of system elements created and shaped by innovation networks.
Source: interviews.

General type	Description	Examples	TIS function positively affected
R&D and field-test support program	Formal institutional structure that provides financial R&D and field-test support	NIP, KGP, regional R&D support of NRW network	Entrepreneurial activities, knowledge development, guidance of search, resource mobilization, market formation, creation of legitimacy (value chain creation)
Vocational training module	Formal institutional structure for the training of professionals in the field	Callux vocational training module	Knowledge diffusion, guidance of search, creation of legitimacy (value chain creation)
Technological standard	Formal institutional structure e.g. for the specification of interfaces	VDI guidelines VDMA preliminary standards	Guidance of search, market formation (value chain creation)
Collective expectation/vision	Cognitive institution that guides actors in the field	[National Development Plan, NEP]	Guidance of search resource mobilization, creation of legitimacy
Technological artifact	Element that embodies technological knowledge and may also serve as a standard	Desulfurization cartridge, standard BOP components	Guidance of search (value chain creation)
Awareness/image	Property of the novel technology	Positive image, awareness of politicians of a stationary application in NIP	Knowledge diffusion, resource mobilization, creation of legitimacy
Intermediary organization	Actor with a particular function in the TIS (e.g. coordination, management, guidance)	NOW GmbH	Knowledge diffusion, guidance of search, resource mobilization, creation of legitimacy (value chain creation)
Network	Formal network with a particular function in the TIS	NOW advisory board	Knowledge diffusion, guidance of search (value chain creation)

generated by other networks. Furthermore, our analysis provided only a one-time review of the structural changes at the system level, which is why we might have missed how the importance of the selected formal networks has evolved and changed over time. Despite these limitations, we believe that our investigation has generated some new and valuable insights for innovation system studies, which we will summarize in the following.

7. Conclusions

Our analysis has shown that formal networks are strategically set up and used by innovating actors in order to create supportive structures for the technological innovation system. In the case at hand, these supportive structures included public R&D programs, modules for vocational training of downstream service providers, technical guidelines, standardized components and an intermediary organization, among others. Furthermore, the networks tried to shape collective expectations and the reputation of the novel technology in a positive way. The activities of the networks and the newly created system elements have been reported to generate benefits for the innovating actors. Public and private financial resources were made available, knowledge was created and deliberately diffused (e.g. through training programs), actors were coordinated and guided towards common goals, linkages between users and suppliers in the value chain were established and the legitimacy of stationary fuel cell technology was strengthened. The various elements contributed to the key functions of the technological innovation system and, thus, increased system performance.

A major lesson we draw from our findings is that the strategic moves of different kinds of actors can have a substantial impact on the development of a technological innovation system. If energy suppliers and technology developers had not joined forces in the IBZ and constantly lobbied for public support, for example, stationary fuel cell technology would certainly have received less attention in the National Innovation Program (NIP) Hydrogen and Fuel Cell Technology. In an emerging technological field, supportive structures and technology-specific institutions can neither be taken as given, nor can they be regarded as being external to technology development. Instead, they are often deliberately created by innovating actors (e.g. with the help of formal networks). The fuel cell case has shown that through collective action, actors might well be able to substantially shape and coordinate the build-up process of an emerging field and that collaboration in formal networks can be a crucial means in this regard.

However, we cannot claim that the observed processes of ‘system creation’ are only possible with a formal coordination of actors in networks. Comparable achievements may also be possible on the basis of a less formal collaboration of actors. In their explanation of the success of the wind turbine industry in Denmark, for example, Garud and Karnoe (2003) refer to the concept of ‘distributed agency’ as a basis for the collaboration of technology producers, users, evaluators and regulators in developing specific design heuristics, testing standards or regulatory schemes. Similarly, Van de Ven (2005) uses the metaphor of innovators who ‘run in packs’ to create an infrastructure for innovation.

In conceptual terms, we have positioned our study in the literature on technological innovation systems. Interestingly, our empirical findings also allow us to draw some conclusions for the underlying theoretical framework.

7.1. Contributions to the literature on technological innovation systems

Our contributions to the development of the TIS concept are threefold. In the recent TIS literature, scholars have made quite an effort to develop a set of functions to assess the various aspects of TIS performance (cf. Section 2). It is expected that the established sets of system functions can cover all essential activities taking place in a technological innovation system (Bergek et al., 2008a; Hekkert et al., 2007). However, our analysis has shown that building up organizational structures and establishing a value chain, or value network, can be a crucial task, especially in an emerging, partly immature technological field. It was reported that actors in the field of stationary fuel cells had an interest in attracting newcomers in order to foster inter-firm collaboration (e.g. between manufacturers and component suppliers) and to create complementary, competences throughout the emerging value chain. As a consequence, they expected specific products and services as well as (sub-)markets to develop. The underlying issue here is the structuring of the innovation system and the creation of a value chain. So far, this aspect has not been well covered by the existing set of innovation system functions. We therefore suggest devoting further attention to this issue in subsequent studies, addressing the question as to how far value chains (or broader value networks) are strategically created and shaped by key actors in a field.

Second, our study has highlighted the potential importance of formal innovation networks in emerging technological systems. Inter-firm alliances, larger associations and other forms of formal collaboration may not just play a role for their members, but also for the development of the TIS as such. While in the case of stationary fuel cells, we have observed sizable some task-sharing among the networks (cf. Section 5.2), a more competitive relationship between different networks is possible as well. Both aspects refer to the broader issue of what different formal networks are capable of. In our study some formal networks were able to conduct multiple tasks whereas others just had a very specific and limited influence on the TIS. Therefore, the question arises as to how some networks develop a specific set of competences. How are organizational resources combined at the level of formal networks to achieve specific tasks? Further research in this regard will certainly improve our understanding of the role of formal networks in emerging technological fields and, thus, connect the network performances with outcomes at the system level (Musiolik et al., submitted for publication).

Finally, and most importantly, our findings offer a complementary perspective on the build-up process of technological innovation systems. The issue that firms strategically join forces to achieve common goals has not been very prominent in the current literature on technological innovation systems. Accordingly, system growth and development, as well as the emergence of positive externalities have been primarily regarded as the result of the enlargement of the actor base and co-location effects (cf. Section 2.1). This is certainly the case. However, our analysis has highlighted that system development and the generation of positive externalities may not just be side effects. Instead, they may be deliberately enacted by key players (or networks) in the field with decisive consequences. Strategically created system elements such as technological standards may represent a supportive institutional structure for some actors, while at the same they time they may impede the development of competing technological variants (e.g. Funk and Methe, 2001; Garud et al., 2002). The example shows that innovation system studies will benefit from analyzing the role of agency and strategic action in some more detail (Markard and Truffer, 2008a, 2008b).

With our complementary perspective we open up many issues related to organizational strategies. For example, we have to deal with the question as to why (some) firms make a commitment and collaborate in networks in order to establish certain structures in the emerging field. This view also opens up a link to the literature on strategic management. The resource based view analyzes the internal (Barney, 1991; Wernerfelt, 1984) and relational (Dyer and Singh, 1998; Gulati, 1999) success factors (resources) of firms. In TIS, system elements that have been deliberately created and shaped can also be perceived as collective resources, which – to a varying degree – are strategically relevant to the innovating firms. Resources such as a training module or a specific support program have to be created to effectively affect suppliers and service providers. Technological knowledge that is made available through technical guidelines or standardized products, technology reputation as well as support programs are valuable resources that many TIS actors can draw upon and that can be expected to improve their position compared to others in competing technological fields (e.g. competing micro-CHP technologies) in which such resources do not exist. In other words, resources are not just strategically created and managed at the organizational level, but also beyond firm boundaries in industries (Foss et al., 1995), networks (Gulati, 1999), or systems. Therefore, we propose to introduce the term 'system resources' in TIS. The introduction and extension of the 'resources' term in the TIS might be beneficial and may provide new insights about the explanation of the dual relationship between firm strategies and the emerging system-level characteristics of TIS.

7.2. Implications for further research and policy making

In this paper, we have addressed the issue of how technological innovation systems are strategically shaped by innovating actors. For the formulation of policies that support novel technologies this topic is highly relevant. Our analysis has shown that a coordination of actors can be crucial for creating supportive structures at the innovation system level. This is in line with existing calls to strengthen networking in emerging technological fields (e.g. Jacobsson and Johnson, 2000; Mans et al., 2008) and collaboration among different kinds of actors (e.g. Garud and Karnoe, 2003; Van de Ven, 2005). Policies that stimulate innovation and also strengthen inter-firm cooperation, therefore, seem to be particularly interesting in order to foster far-reaching changes and sectoral transitions (cf. Kern and Smith, 2008; Nill and Kemp, 2009).

We have to keep in mind, though, that our study represents just one building block in a broader research agenda on the role of actors in innovation system studies (Markard and Truffer, 2008a) and that we are still far from formulating full-fledged policy recommendations. To our knowledge current studies do not study in detail how positive externalities are created or how innovating firms shape their environment. Also, against this background, our study opens up a new perspective for analyzing success and failure of new, immature technologies. In future research, it might thus be particularly interesting to look at the resources firms mobilize to create and shape TIS structure and to analyze the conditions which motivate firms to commit themselves to 'system creation'. In addition to that one may ask which actors or networks can take the lead in such processes of system formation and under what conditions. Are there particular networks that produced particular kinds of system resources? Are there specific actor constellations that are highly beneficial for generating positive externalities? And what are potential downsides for committed actors, e.g., in terms of free-riding competitors?

To fully address these questions, to reap the benefits of studying collective resources at the level of innovation systems and to arrive at sound policy recommendations much work is still needed. However, the successful accomplishment of this research agenda will increase the understanding of micro-meso-level linkages and thus uncover important determinants of innovation success.

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