Innovation system-building: on the role of actors, networks and resources

The case of stationary fuel cells in Germany

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Innovation system-building: on the role of actors, networks and resources

The case of stationary fuel cells in Germany

Het opbouwen van innovatie-systemen: over de rol van actoren, netwerken en middelen

De casus van stationaire brandstofcellen in Duitsland

(met een samenvatting in het Nederlands)

Proefschrift

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door

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"If I had asked people what they wanted,

they would have said faster horses."

(Henry Ford)

Contents

Summary

In the field of energy supply, various innovative technologies such as fuel cells, photovoltaics and biomass digestion exist as potentially sustainable alternatives. However, many of these new technologies only cover small percentages of the overall energy supply. A better understanding of the determinants of innovations is thus crucial for their timely diffusion and a subsequent transformation of the energy sector towards more sustainable technologies. To examine the complex dynamics of technological change, the concept of technological innovation systems (TIS) represents a fruitful approach. TIS studies focus on the interplay of actors, networks and institutions and reveal systemic blocking or enhancing mechanisms that impact the generation, utilization and diffusion of new technologies.

In this stream of literature, agency and the structural build-up of TIS have not been a focus point, despite their significance for innovation processes. This dissertation explores the relationships between the strategic moves of actors and the development of new technological fields. To address this question, we draw on ideas and concepts from the strategic management and entrepreneurship literature and combine them with the innovation systems perspective. In particular we focus on resources and their role in innovation system-building. The empirical field of inquiry is the innovation system on stationary fuel cells in Germany. Through in-depth interviews with key informants directly involved in system-building, we studied the strategies of firms and formal networks in the field.

The field of stationary fuel cells in Germany represents a very interesting case, as the technology is not only important for the development of a smart energy system but also indicative of many technological and organizational problems currently faced by (energy) innovations as they progress from prototypes to a mass market. Our analysis revealed how key actors and networks strategically influenced the emergence of the TIS and shaped the structures of the new field. They created technological standards, lobbied for public support programs, set up commonly available training modules, created value chains and increased public awareness of fuel cells. These structures represent assets that are of strategic value for firms interested in the novel technology. We conceptualize them as system resources. Our research shows that some specific actors, which we refer to as system builders, have continuously pushed the development of collective resources at the network and system level. Network resources such as joint knowledge, reputation, power and governance structures, in addition to the aforementioned system resources, are strategically developed and deployed to influence and control the development of the innovation system as a whole.

Our empirical insights and conceptual reflections complement the existing concepts used in innovation system studies. By elaborating on different kinds of resources at the

organizational, network and system level, and delineating strategies of system-building, we have made a major contribution to the technological innovation systems framework. This thesis represents a key element in the emergent research agenda on micro-meso level processes in emerging technological fields. Moreover, the developed framework and knowledge might help to improve the design of public policies and technological support programs, in order to accelerate the market entry of clean technologies and foster the transition of the energy supply system in industrialized societies.

Samenvatting

Op het terrein van de energievoorziening zijn er verschillende innovatieve technologieën zoals brandstofcellen, fotovoltaïsche cellen en biomassavergisting die de potentie hebben uit te groeien tot duurzamere alternatieven voor bestaande niet duurzame technologie. Om te komen tot een duurzame energievoorziening hebben we vele van deze alternatieven nodig aangezien elk maar een klein deel van de toekomstige energievraag kan vervullen. Een beter begrip van de factoren die invloed hebben op de snelheid van innovatie en diffusie is nodig om zorg te dragen voor hun tijdige diffusie en daarmee de transformatie naar een meer duurzame energiesector te bewerkstelligen. Om de complexe dynamiek van technologische verandering te bestuderen is het Technologische Innovatie Systeem (TIS) heel geschikt. TIS studies concentreren zich op het samenspel tussen actoren, netwerken en instituties en leggen de systemische mechanismen bloot die de ontwikkeling, het gebruik en de verspreiding van nieuwe technologieën vertragen dan wel versnellen,.

In deze stroming in de literatuur zijn het gedrag van individuele actoren tot nu toe onderbelicht gebleven, dit ondanks hun grote belang voor innovatieprocessen. Deze dissertatie gaat hier juist wel op in en onderzoekt de relaties tussen de strategische bewegingen van actoren en de ontwikkeling van nieuwe technologische velden. Om dit te realiseren maken we gebruik van ideeën en concepten uit de innovatieliteratuur, respectievelijk over strategisch management en ondernemerschap. Deze combineren we met het innovatiesysteem concept. In het bijzonder concentreren we ons op rol van *resources* (middelen) in de opbouw van innovatiesystemen. Het empirische veld van onderzoek is het innovatiesysteem rondom stationaire brandstofcellen in Duitsland. Door middel van diepte-interviews met sleutelspelers die direct betrokken zijn geweest bij de opbouw van het systeem hebben we de strategieën van zowel bedrijven als formele netwerken bestudeerd. De casus van stationaire brandstofcellen in Duitsland is zeer interessant, omdat de technologie niet alleen belangrijk is voor de ontwikkeling van een slim energiesysteem maar ook indicatief is voor de vele technologische er organisatorische problemen waarmee andere (energie-) innovaties momenteel ook geconfronteerd worden in de stap van prototype naar massamarkt. Onze analyse laat zien hoe de belangrijkste actoren en netwerken op strategische wijze de opkomst van het TIS hebben beïnvloedt en hoe ze de structuur van het technologisch veld vorm hebben gegeven. Ze hebben technologische standaarden gecreëerd, gelobbyd voor publieke ondersteuningsprogramma's, algemeen verkrijgbare trainingsmodules opgezet, waardeketens gecreëerd en hebben meer publieke bekendheid gegeven aan brandstofcellen. Deze structuren vertegenwoordigen strategisch waardevolle activa voor bedrijven die belangen hebben in de nieuwe technologie. Wij conceptualiseren deze als *system resources of in goed Nederlands 'collectieve middelen'*. Ons onderzoek laat zien dat een aantal specifieke actoren, die wij systeembouwers noemen, continu hebben

aangedrongen op de ontwikkeling van collectieve middelen op het netwerk- en systeemniveau. *Netwerk middelen* zoals gedeelde kennis, reputatie, macht en governance structuren, worden in aanvulling op de eerdergenoemde *collectieve middelen* strategisch ontwikkeld en ingezet om de ontwikkeling van het innovatiesysteem als geheel te beïnvloeden en te controleren.

Onze empirische inzichten en conceptuele bespiegelingen vormen een aanvulling op de bestaande concepten die gebruikt worden in innovatiesysteemstudies. Door het uitwerken van verschillende soorten middelen op het organisatorische-, netwerk- en systeemniveau en door het beschrijven van strategieën voor systeemopbouw, hebben we een bijdrage geleverd aan het Technologische Innovatie Systeem concept. Deze dissertatie draagt bij aan de opkomende onderzoeksagenda op het terrein van de dynamiek van micro meso interactie in emergente technologische velden. Bovendien, het ontwikkelde raamwerk en de opgedane kennis kunnen bijdragen aan de verbetering van het ontwerp van beleid en technologische ondersteuningsprogramma's die tot doel hebben de marktintroductie van schone technologieën te versnellen en de transitie van het energievoorzieningssysteem in geïndustrialiseerde samenlevingen te bevorderen.

List of publications

This thesis is based on the following publications:

Musiolik, J., Markard, J., Hekkert, M. P. (to be submitted) Technological innovation and deliberate system-building: the case of stationary fuel cells in Germany.

Markard, J., Musiolik, J., Worch, H., 2011. System resources in emerging technological fields: Insights from resource-based reasoning for innovation and transition studies, 2nd International Conference on Sustainability Transitions, Lund.

Musiolik, J., Markard, J., 2012. Collective resources in technological innovation systems in: Decker, M., Grunwald, A., Knapp, M. (Eds.), Der Systemblick auf Innovation - Technikfolgenabschätzung in der Technikgestaltung. edition sigma Berlin, pp. 129-140.

Musiolik, J., Markard, J., Hekkert, M.P. (2012) Networks and network resources in technological innovation systems: towards a conceptual framework for system-building. Technological Forecasting and Social Change 79, 1032–1048.

Musiolik, J. (2011). External innovation management of energy service providers in Germany. Network Industries Quarterly. Vol. 13, no 2. 14-17.

Musiolik, J., Markard, J. (2011). Creating and shaping innovation systems: Formal networks in the innovation system for stationary fuel cells in Germany. Energy Policy 39,1909–1922.

List of abbreviations

Callux	Field test network of stationary fuel cells in Germany
CHP	Combined Heat and Power
FC	Fuel Cell technology
CFCL	Ceramic Fuel Cells Limited
IBZ	IBZ fuel cell initiative
MEA	Membrane Electrode Assembly
NEP	National Development Plan Hydrogen and Fuel cells
NIP	National Innovation Program (NIP) Hydrogen and Fuel Cell Technology
NIS	National Innovation Systems
NOW	National Organization Hydrogen and Fuel Cell Technologies
NRW	North Rhine Westphalia
LTS	Large Technical Systems
KW	Kilowatt
PEM FC	Proton Exchange Membrane Fuel Cell
RIS	Regional Innovation System
R&D	Research and Development
SCOT	Social Construction of Technology
SOFC	Solid Oxide Fuel Cell
TIS	Technological Innovation System
VDI	Association of German Engineers
VDMA	German Engineering Federation
ZBT	The fuel cell research center ZBT GmbH
ZSW	Center for Solar Energy and Hydrogen Research Baden Württemberg

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1 Introduction

Modern societies are currently encountering large problems in different but interrelated spheres such as energy security, climate change and economic development. The paradigm of an industrial age based on cheap fossil sources of energy is increasingly under pressure. Limited fossil resources and continuing consumption will lead to even higher energy prices with strong repercussions on economic growth (Rifkin, 2011). In addition to that the combustion of fossil fuels causes various environmental problems: air pollution, acidification of the biosphere, and global warming. According to the lowest emissions scenario of the Intergovernmental Panel on Climate Change (IPCC), the global surface temperature is likely to rise a further 1.1 to 2.9 °C during the 21st century and thus leads to extreme weather events such as coastal flooding, reductions in water supplies and an increased health impact with additional losses in economic growth and development (Pachauri, 2007).

Technological change and the development of clean technologies are seen as part of the solution to the current ecological and economic crisis. Clean technologies or so-called eco-innovations, such as fuel cells, wind energy, photovoltaics and biomass digestion, are more efficient either in their conversion of fossil energies or their use of renewable sources of energy; they are designed to reduce CO_2-emissions and to increase energy security. In addition, the convergence of internet communication technologies and decentralized (clean) technologies might even lead to industrial evolution and an entire new energy system which is interactive, integrated and seamless (Rifkin, 2011). New industries might emerge as the interconnectedness of new energy systems generates new opportunities for cross-industry relationships and the development of new business opportunities (ibid). Hence, politicians are designing climate policies to influence the economy. In addition they are proposing a ‘Green New Deal’ to combine different policies and foster an ecological transformation of capitalism in the aftermath of the financial crisis in 2008 (Barbier, 2010).

The transition towards a sustainable energy supply system, however, is a complex long-term process (Geels et al., 2004; Berkhout et al., 2004; Smith et al., 2004). Despite their technological and economic potential, various clean technologies still only cover small percentages of the overall energy supply (De Vries et al., 2007; Hoogwijk, 2004; Rogner, 2000). Conventional, centralized power plants based on fossil fuels still dominate the scene. In fact the energy supply sector has evolved over the last decades into an interlinked socio-technical complex or system of interconnected components such as technical artifacts, manufacturing firms, utility companies, investment banks and academic research (Markard, 2011). This complex continuously provides positive reinforcement (e.g. economies of scale, network externalities, accumulation of knowledge etc.) in support of carbon based energy technologies, and constitutes a ‘carbon lock-in’ (Unruh, 2000).

Many decentralized clean technologies are radically different to the dominant mode of central energy generation (and the underlying technological paradigm). Their diffusion requires substantial changes on the supply side (how firms, suppliers, research institutes etc. interact and combine knowledge), as well as the user side and the final distribution of the product or service (Geels et al., 2004). On the user side, decentralized clean technologies such as photovoltaics, biogas or stationary fuel cells are currently challenging established markets and distribution channels.[1] On the supply side, knowledge and competences from different sectors have already been creatively combined to realize new technologies. Different prototypes or small batch products are currently entering the market while new value chains and markets slowly evolve. In fact new technological fields or 'green industries' emerge as suppliers, manufacturers and service providers become interlinked in effective value-chains, and are able turn prototypes into reliable mass products with a competitive price.

The step from prototypes to mass production is critical for many clean technologies. They face several interrelated problems as markets and value chains are not easily formed. Compared to incumbent technologies new (immature) technologies have a cost disadvantage (Jacobsson and Bergek, 2004). As they are produced in low numbers and in low quality, clean technologies have currently difficulties to enter the established markets. Moreover, existing market structures do not account for the benefits these technologies provide: clean technologies do not offer any direct benefits for individual buyers or investors, but rather for society as a whole (Jacobsson and Bergek, 2004). Another important point is that innovating firms, which depart from established economic activities, cannot build on established routines, standards, suppliers, services and maintenance structures on the supply side, nor interested customers and developed distribution channels on the user side. In fact proponents of clean technologies have to deal with high uncertainties in terms of regulations and support of politicians as well as the commitment of complementary firms (suppliers, fitters and other service providers etc.). Suppliers, for example, only invest in the mass production of components of new technologies if there is a market with a large sales volume, while manufacturers of clean technologies strongly depend on a division of labor to increase quality and reduce the price of the end product.[2]

In this thesis we do not focus in particular on the competition between incumbent and clean technologies. We are solely interested in the process of technological innovation and the emergence of new technological fields. Clean technologies do not just depend on

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[1] Passive consumers of electricity and heat might turn into users which who actively shape the development of technologies and of new business opportunities.

[2] The same holds true for the role of policy makers, on whose commitment innovating firms are dependent; the firms must count on governmental support in order to compete with (subsidized) incumbent technologies, and to internalize some of the positive externalities of clean (energy) technologies.

the development of a technology or prototype, but also on the establishment of a wider social system or entrepreneurial infrastructure in which the technology is embedded (Van de Ven, 1993; Van de Ven and Garud, 1989). Technology-specific support structures such as dominant designs (Murmann and Frenken, 2006) technological standards, test to determine the value of a novel technology, technology-specific regulations and funding schemes in addition to functional value chains and effective service structures have to co-evolve with the technology in order to decrease the liability of newness.[3]

The emergence of supportive socio-technical complexes or systems has been studied in different streams of literature (Bijker et al., 1987; Garud and Karnoe, 2003; Hughes, 1979; Hughes, 1987; Jacobsson and Bergek, 2004; Jacobsson and Lauber, 2006; Lundgren, 1995; Möller, 2010; Van de Ven, 1993; Van de Ven and Garud, 1989). Two general accounts of how new technological fields evolve can be differentiated. For some authors, the process of industrial evolution is a rather a complex, uncoordinated process, in which many different activities of distributed firms and other organizations contribute to the emergence of new technologies, value chains and complementary institutional structures such as standards, dominant designs or effective market structures (Garud and Karnoe, 2003; Lundgren, 1993). Others, however, stress the role of individuals and the intentional strategies and activities of key actors (Hughes, 1979; Möller, 2010). In this literature, so-called system builders are not only concerned with the development of a specific technology but also initiate and steer the development of supportive socio-technical systems.

In our view, supportive socio-technical systems can neither be taken for granted nor treated as being external to the process of technology development. Instead they are often created and shaped by dedicated actors. In this thesis we therefore focus on the coordinated intentional activities, and explore the relationship between strategic moves of firms and other organizations and the development of new technological fields. In particular, we seek to study the strategies available to system builders for influencing, e.g. the formation of value chains, support programs and the establishment of technological standards, and thus to manipulate technology innovation and the build-up of a new technological field.

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[3] Moreover, as with the established incumbent technologies in energy supply, also here supportive socio-technical complexes have to co-evolve with clean technologies to provide positive reinforcements, decrease uncertainty and enhance their chances of success. In fact, to increase the chances of success of clean technologies, supportive structures have not just to co-evolve but must also interrelate functionally as components of a technology-specific system. Positive reinforcement cycles are important for the emergence of a technology field (Bergek et al., 2008a; Hekkert et al., 2007). Supportive structures facilitate innovation, induce the ‘entry’ of new actors and thus stabilize and legitimize a new technology.

In empirical terms we analyze the build-up of the field of stationary fuel cells in Germany. The fuel cell technology has a high potential to reduce the usage of fossil sources of energy and CO_2 emissions and may even lead to the emergence of new industries (Vasudeva, 2009). In Germany and other countries initial activities in the field of fuel cells already lead to various pilot plants, extensive field tests and to activities in market formation (Brown et al., 2007; Markard and Truffer, 2008a; Nygaard, 2008). While the formation phase of the technological field took more than 30 years, firms and other organizations in Germany are currently moving towards a breakthrough phase with clear strategies for commercialization of the fuel cell technology (Nygaard, 2008).

We conducted interviews with key informants, identified formal networks and other key organizations which contributed to system-building, and also studied in detail how these actors proceeded strategically. Accordingly, we did not only identify different types of activities towards system build-up but also studied in detail the means or resources on which these different organization have drawn on to accomplish their aims in system-building.

Our results help to increase the understanding of the link between the emergence of technological fields and the activities and strategies of firms and other organizations. We provide a foundation for the analysis of strategies in the build-up of supportive socio-technical structures. By identifying viable strategies of system builders, we can better detect their abilities and limits and thus better differentiate between the respective roles of firms and public policy makers in technological innovation. In addition, we would like to inform managers on the strengths and weakness of the different strategies of system builders, and politicians on how they can better support key system builders and the specific technology trajectories which they create and shape.

1.1 Theoretical foundations

Technological innovation and the emergence of new technological fields cannot just be explained by the occurrence of new process- or product innovations (Schumpeter, 1934). It also depends on the co-evolution of new markets, new organizational structures and new institutions (Markard & Truffer, 2008b). Innovation system (IS) concepts cover the interplay of these changes at different levels. They are deeply rooted in evolutionary economics (Nelson and Winter, 1982) and acknowledge interdependences, non-linarites and interactive learning (Lundvall, 1992).

IS approaches are based on the idea that determinants of innovation processes are not only located at the level of innovating firms but also embedded in the broader societal environment in which firms and complementary actors are embedded (Carlsson and Stankiewicz, 1991). Innovation system concepts were developed for different purposes and foci of analysis. They include national innovation systems (NIS) (Freeman, 1997; Lundvall, 1992 Nelson, 1988), regional innovation systems (RIS) (Cooke et al., 1997), sectoral innovation systems (SSI) (Breschi and Malerba, 1997; Malerba, 2002) and technological innovation systems (TIS) (Carlsson and Stankiewicz, 1991; Markard and Truffer, 2008b). For an overview c.f. (Carlsson et al., 2002b; Edquist, 1997; Musiolik, 2007). What the different concepts have in common is that they account for non-linearities, a close interaction of various system components and a key role for institutional structures in innovation dynamics (Carlsson et al., 2002b; Ylinenpaa, 2009).

1.1.1 Technological innovation system

The emergence of new technological fields can be studied with the technological innovation system framework. In contrast to NIS and RIS, which focus on a geographical unit of analysis, the TIS approach focuses on a selected technology and sets the system boundaries accordingly (Carlsson and Stankiewicz, 1991 Ylinenpaa, 2009).

A technological innovation system can be defined as 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" (Markard and Truffer, 2008b, 611). Actors encompass individuals and organizations that contribute to the development of the technology (Hellsmark and Jacobsson, 2009). In contrast to neoclassical theory, the heterogeneity of actors is pronounced: actors include different kinds of firms, research institutes, financial institutions, associations, governmental agencies or policy makers each with specific competences, resources and strategies (Carlsson and Stankiewicz, 1991). Networks interlink different actors and often emerge as non-market relationships in which interactive learning (e.g. user-supplier or university-industry networks) and the formation of political networks is key (Bergek et al., 2008a; Jacobsson and Lauber, 2006). Finally, institutions set the "rules of the game" (North, 1990) which regulate the relations and interactions between individuals, groups and organizations (Edquist, 2005), for example by defining which kinds of activities are desirable and legitimate.

Early TIS studies focused on system structures, while later work has concentrated on key processes or system functions as the core unit of analysis. (Bergek et al., 2008a; Hekkert et al., 2007; Suurs and Hekkert, 2009). Structures and key processes which supported or hampered the development of a particular technology have been analyzed in empirical studies, and evaluated to inform decision makers (Negro and Hekkert, 2008; Negro et al., 2008; Suurs and Hekkert, 2009; Suurs et al., 2010). Subsequently, politicians should design interventions to overcome structural barriers and reinforce the key process of the TIS (Bergek et al., 2008a).

1.1.2 Shortcomings of current TIS studies

Current research on TIS has its strengths in the analysis of system structures and functions. This emphasis on the meso-level is due to the fact that the TIS concept was developed with the intention of complementing the existing literature on firm strategy with the collective and systemic aspects of innovation (Jacobsson and Bergek, 2004). Indeed, the value added by the TIS framework is that it provides a better understanding (and a better analytical focus) of the non-linear dynamics in emerging and also mature technological fields. Characteristics of established technological fields such as value chains, entry barriers or competitive relationships are regarded as emergent components and as a result of uncoordinated processes at the system level.

This approach to the study of new technologies has some shortcomings: firstly, TIS scholars tend to be more interested in TIS performance than in how the existing structures came about. It is taken for granted that some kind of system is already established around a new technology. As a consequence, both the formative phase of a TIS and the processes of system formation are still poorly understood in the literature (cf. Jacobsson and Bergek, 2004; Nygaard, 2008). Secondly, actors are currently introduced as structural elements of a TIS. They are conceptualized as actor groups, as representatives or agents of their sectors with specific competences (Bergek and Jacobsson, 2003). Agency does not play a pivotal role. Moreover, the current TIS framework can neither explain why actors differ in their importance nor why some actors strategically contribute to system build-up (Hughes, 1979). Thirdly, positive externalities are identified as an important condition for innovation (Bergek et al., 2008a; Jacobsson and Bergek, 2004). They are conceptualized as quasi-automatic side effects of an accumulation of actors and 'critical mass' (cf. Bergek et al., 2008a; Jacobsson and Bergek, 2004).[4] Due to this focus, the contributions of actors and the *deliberate* provision of positive externalities are not studied in any detail. Fourthly, coordination of actors is equally regarded as emergent and the coordinative capacity of a TIS is captured by the system function 'guidance of the search' (Bergek et al., 2008a; Hekkert et al., 2007). Consequently, strategic activities towards coordination and the integration of complementary actors tend to be overlooked. TIS studies do not focus on the creation and manipulation of value networks or business fields (Möller, 2010).

In summary, the current framework does not pay much attention to the fact that innovation systems are also deliberately shaped and created, and that actor strategies and the entrepreneurial process of system-building have much influence on subsequent system performance (Markard and Truffer, 2008a; Musiolik and Markard, 2011). TIS studies do not take into account determinants which influence the activities of actors towards TIS build-up.[5] We will argue that in order to foster the development of novel technologies, it is important to follow he strategic moves of actors and to analyze the conditions under which they join forces and establish supportive TIS structures. In particular, the TIS concept

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[4] The same holds true for the emergence of specific labor markets, service providers or knowledge spill-overs which are also explained by an enlargement of the actor base or co-location effects (ibid).

[5] As an example, we expect that the absence of crucial actors might hamper innovation or that collective action depends on the coordination of actors and an infrastructure for collective action, i.e. functional networks in the field.

lacks a framework which helps to explain the strategic moves of actors or why actors deliberately contribute to the creation of supportive systems structures. This is of importance as we can expect free-riding and other first mover disadvantages (burnout of the pioneers) which might hamper the development and diffusion of new technologies (Hellsmark and Jacobsson, 2009; Lieberman and Montgomery, 1988; Olleros, 1986).

1.1.3 A perspective towards deliberate system-building

We will argue that a TIS does not just emerge as a quasi-natural phenomenon. Instead, specific TIS structures are also deliberately created and shaped by some actors. In our view, a TIS is not only a heuristic or analytical construct of researchers (Carlsson et al., 2002b; Edquist, 2004). It also resides in the minds of actors or system builders dedicated to technology entrepreneurship (Hughes, 1979; Hughes, 1983; Hughes, 1987).

If the concept is properly applied it can be used to capture the interaction of a specific population of firms and the supportive environment they are embedded in (Suurs, 2009). In fact, the degree to which actors are conscious of being part of an emerging field or innovation community (Lynn et al., 1996) will influence how they perceive properties of a TIS and consciously engage in system-building.[6] In this thesis we therefore analyze the system-building activities of selected actors in a TIS, and introduce the concept of deliberate system-building, i.e. that key actors deliberately contribute to the creation of supportive system structures in order to support technology development.

That technology specific support structures are created and shaped is also acknowledged in the strategic management and entrepreneurship literature (Sarasvathy and Dew, 2003; Sarasvathy, 2008; Sarasvathy and Dew, 2005; Van de Ven, 1993, 2005; Wiltbank et al., 2006). This literature and TIS studies have in common a focus on the interplay of actors, and study the same phenomena: emergent business fields or markets. Today firms do not just position themselves in fixed set of activities or markets, but also explore and develop value creating systems (Ramirez, 1999) and thus steer the co-creation of new markets (Sarasvathy and Dew, 2005). Therefore, in the area of new products, new market combinations (radical innovations), firms realize that the set-up of new business opportunities is a complex process which depends on the commitment of complementary actors and collective action. Innovating actors, subsequently, follow a system-building approach as they intentionally set up (business) networks, value creating systems and broader (institutional) structures to realize new business opportunities (Hajek et al., 2011 Normann and Ramirez, 1993).

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6 Especially in the case of radical innovation, in which resources, knowledge and competences of established sectors have to be combined or transformed, perceived supportive structures might guide the strategic activities of actors in system formation (Van de Ven, 1993).

A crucial determinant of the innovation and system-building activities of firms are the means or resources they have at their disposal and the strategy they pursue. On the one hand, strategy is concerned with the deployment and configuration of resources, processes and organizational structures in order to reach a specific goal. On the other hand, strategy also depends - amongst other factors - on the resources and competences readily available in a firm.[7] The resource-based view (RBV) is a well-established approach which takes these two features of strategy into account to explain strategic maneuvers and the competitive advantage of firms. Organizational resources such as patents, technological knowledge or firm reputation are strategically developed and accumulated within firms and deployed to realize business strategies (Barney, 1991; Dierickx and Cool, 1989; Kraaijenbrink et al., 2010). Resources, in other words, provide services (Penrose, 1959) and set limits to what a firm can do (Rumelt, 1984b). While resources at the organizational level are certainly a focus of the management literature, the resource concept has also been applied to higher levels of aggregation including inter-firm networks (Dyer and Singh, 1998; Gulati, 1999) and industries (Foss and Eriksen, 1995). The broader environment firms operate in can in fact be thought of as “a large external resources and capabilities space” (Foss and Eriksen, 1995, 45).[8]

This general line of thought is also important for the study of innovation systems, in which emergent properties of technologies (e.g. norms, standards, collective expectations, the reputation of a technology) have been identified as key factors in the innovation process. Recently the literature of strategic management acknowledged moving from a rather “objective” or external definition of resources to one defined by the situation or the context (Kraaijenbrink et al., 2010). Accordingly, the value of a resource is a matter of strategic judgment and depends entirely on the degree to which management did succeed in capturing resource synergies (Mathews, 2002). The same resource can have a different value for a firm at different points in time. Therefore, what is valuable for firms in innovation depends on the context and the strategies of the innovating firms.

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[7] “Strategy can be defined as the determination of the basic long-term goals and objectives of an enterprise, and the adoption of courses of action and the allocation of resources necessary for carrying out these goals.” (Chandler, 1962, 13). However, strategy does not necessarily have to be based on a specific plan. A firm can, for example, perform a series of concerted, but unplanned activities of strategic character, which in the end turn out to be (or are interpreted) as strategy (emerging strategy). As a consequence, Mintzberg (1987) proposes a more complex model of strategy including plan, pattern, position, perspective (or vision) and ploy.

[8] In subsequent studies not only the lack of applicability of the RBV in highly dynamic markets (Kraaijenbrink et al., 2010), but also the definition of resources based on a traditional understanding of firm boundaries was criticized (for discussion of the shortcomings of the RBV we refer to (Barney, 2001c; Priem and Butler, 2001a, b).

We thus assume that innovating firms not only establish and use resources at the organizational level, but also develop and deploy resources in the broader innovation system. In the case of radical innovations (new product/new market combinations) where the departure from established paths, technologies, markets or practices is accompanied with ambiguity[9] and high uncertainty (Meijer et al., 2007a, b; Santos and Eisenhardt, 2009), resources which firms have at their disposal or can access in their environment might be a starting point for creating and shaping supportive TIS structures. These structures in turn increase the chances of success of new technologies while reducing ambiguity and uncertainty.

This idea is in line with current calls in the literature of entrepreneurship (Sarasvathy and Dew, 2003; Sarasvathy, 2001; Sarasvathy and Dew, 2005; Wiltbank et al., 2006). Entrepreneurs might start from the resources they have at their disposal and successively involve other actors in networks to increase the available resources. This strategy -- forging networks of actors and setting up a cycle that increases the resources available -- reduces ambiguity and uncertainty as a technological field is co-created (Wiltbank et al., 2006).

1.1.4 Summary and research questions

It has been argued above that actors and their system-building activities might be crucial in the case of radical innovations and the build-up of new technological fields. Our understanding of system-building departs from the TIS framework, incorporates ideas of Sarasvathy and colleagues (Sarasvathy and Dew, 2005; Wiltbank et al., 2006) and draws in particular on the concept of resources (Barney, 1991; Dyer and Singh, 1998). We develop a model of resource-driven TIS build-up, in which innovating actors follow a system-building strategy: they interact with other actors and slowly create and shape supportive system elements which provide externalities, in addition to facilitating innovation and the commitment of complementary actors.

This approach complements current TIS analysis. The TIS literature devotes little attention towards deliberate system-building strategies, so it is rather unclear how system builders proceed, on what types of resources they draw, and what kinds of system components they can create and shape. TIS elements such as technology-specific standards or support programs cannot only be conceptualized as structural components of TIS but also as system resources which firms can draw upon. In fact, they are supportive structures which facilitate, guide or legitimate the innovation activities of firms in a specific field (Coriat and Weinstein, 2002), which means they tend to be of strategic interest for innovating actors. We expect that key actors create and shape system elements such as

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[9] Ambiguity can be defined as the lack of clarity about the meaning and implications of particular events or situations (Santos and Eisenhardt, 2009). It arises from a lack of recurrent, institutionalized patterns of relations and actions (Hajek et al., 2011).

support programs, value chains or service structures for new technologies. Moreover, system builders do not only develop and deploy resources at the organizational and network level but also on the system level in order to build up a supportive TIS and improve the prospects of the new technology.

Our analytical framework, presented in Figure 1, interlinks the system, network and actor levels. Out starting point is that resources exist at different levels and that firms and other actors come together in networks in order to develop and deploy resources and to create and shape system elements. These system elements or system resources might have an effect on system functioning and on the actor level (indicated through the arrows in the figure). Furthermore, in addition to actors joining networks in order to create and shape system resources, there may be other processes or strategies of system-building (also indicated through an arrow in the figure).

Accordingly, the central research question of this thesis has been formulated as follows: *RQ 1:* How do actors and formal networks influence the build-up of supportive TIS? By focusing on deliberate system-building processes we change the perspective on TIS components such as actors, institutions and networks, and open up many questions related to strategies and the development, deployment and transformation of resources at different levels. Figure 1 therefore also presents the six subsidiary research questions which have guided our analysis of the system-building process.

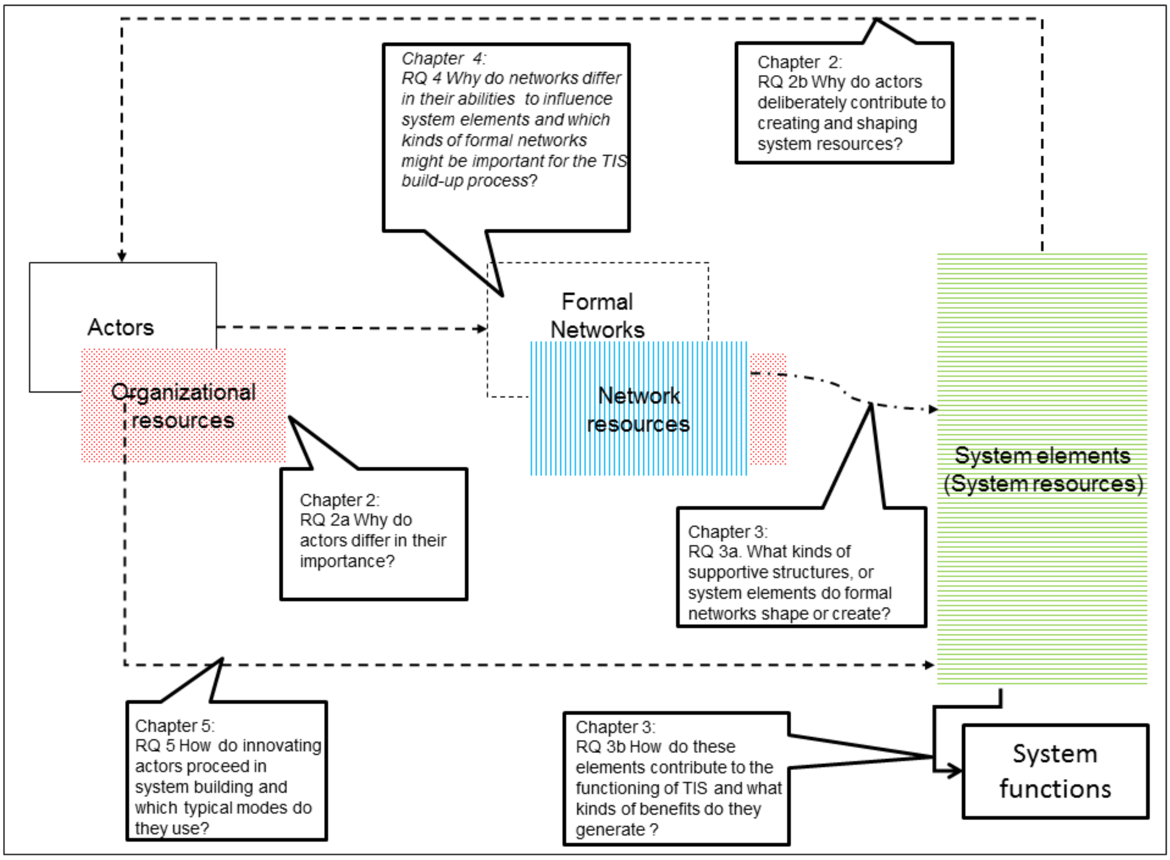

Figure 1: **Subsidiary research questions**

As we are concentrating on actors' strategies and deliberate activities in the TIS build-up, we must first identify empirically the system elements which actors and networks have create and shape (RQ3a). We are also interested in assessing how the created and shaped elements contribute to the functioning of the TIS, and in understanding why actors deliberately contribute to the generation of structural elements which provide benefits for followers (RQ 2b, 3b). Thirdly, we seek to analyze why actors and formal networks might play different roles and differ in their abilities in system-building (RQ2a, RQ4). Finally, as we cannot claim that the processes of 'system creation' are only possible with a formal coordination of actors in networks, we also wish to analyze how system builders typically proceed and what kinds of strategies or modes they typically use to initiate and steer system-building (RQ 5).

1.2 Empirical field

For our empirical study we selected the emerging field on stationary fuel cells in Germany. Fuel cell technology has been recognized for its major technological advantages and its potential to build up new industries (Madsen and Andersen, 2010). In addition to that, it is often considered as an essential element of a sustainable energy system because of its high electricity-to-heat ratio and overall conversion efficiency.[10]

1.2.1 Fuel cell technology

The underlying technological principle is rather old and was already known in the 19th century. Fuel cells are energy converters which transform chemical energy from a fuel into electricity and heat through a chemical reaction. Various types of fuel cells exist which differ in terms of the electrolyte, catalyst materials, operating temperatures, fuel requirements and electrical output (Brown et al., 2007; Harborne et al., 2009; Markard and Truffer, 2008a).

The technology has some key innovation characteristics which affect its application and commercialization. Fuel cells have a high electricity-to-heat ratio and high overall conversion efficiency, a silent operation without moving parts, and low air emissions (Markard and Truffer, 2008a). In contrast to batteries, they produce electricity continually as long as fuel is supplied. Individual fuel cells can be 'stacked', placed in series or parallel circuits. Due to this modular design, they can supply electric power from a few watts up to several megawatts (Carrette et al., 2001). In addition, the technology can use a variety of primary fuels such as natural gas, methanol or biogas, while hydrogen is the most common fuel (Carrette et al., 2001). These advantages of fuel cell technology are

[10] As the demand for heat and fuel is expected to decrease much more than the demand for electricity in the final energy sectors, fuel cell technology is considered a better match for the increasing share of electricity in total energy demand (Bradke et al., 2007).

applied to new products in different industries: in cars and buses (mobile fuel cells), in electronic devices (portable fuel cells) and for the energy supply of buildings (stationary fuel cells).

One can distinguish between stationary fuel cells with industrial application (a capacity of more than 100 KW) and those with small residential fuel cell-based heating applications (between 1 and 5 KW). Both technologies have in common the cogeneration principle, i.e. the combined generation of heat and power (CHP), but they represent separate fields with different standards, manufacturers, suppliers and markets.

Small residential fuel cell-based heating devices, so-called micro CHP systems, have the potential to replace conventional boiler technology and to enter the mass market in the long term. They are ideally suited to single and two-family homes, as the produced heat can be used directly for hot water and heating purposes. Different variants of fuel cell micro CHP systems exist and differ in terms of the electrolyte, catalyst materials as well as operating temperatures and electrical output; the SOFC (solid oxide fuel cell), low temperature PEMFC (proton exchange membrane fuel cells, also known as polymer electrolyte membrane fuel cells) and high temperature PEMFC variants are currently promising in this output range (Hendry et al., 2008).

1.2.2 Selection of the research site

Fuel cell manufacturers and component suppliers are widely active in different countries. Although multi-nationals such as 3M and BASF are increasingly active on a global scale, national institutions such as R&D programs, research institutes and lead markets are still of crucial importance in the field. Countries such as Japan, USA, Germany and Korea play a key role in terms of public funding and the support of fuel cells. Although the fuel cell is a technology in an early stage of development, and until has only been applied in pilot projects and field tests (Adamson, 2005; Adamson and Crawley, 2006), contours of a technological innovation system are already visible in these different countries (Hendry et al., 2007; Markard and Truffer, 2008a; Nygaard, 2008).

The field of stationary fuel cells in Germany represents a particularly fruitful case to study the activities and strategies of actors and the role of networks and system builders. Germany is a leading country in the development of clean technologies as well as the field of fuel cells (Weider et al., 2003). Furthermore, it is known for its institutional environment which fosters the cooperation of firms and establishment of associations and industry fares (Vasudeva, 2009).

Important structural elements have been established, but the TIS is still in the formation phase. Although the technological principle of fuel cells is rather old, system builders in Germany were only recently able to instill its societal value for solving the climate and energy problem. System builders, in other words, have been very successful in convincing public authorities and other industry members to set up a specific NIP support program (National Innovation Program (NIP) Hydrogen and Fuel Cell Technology). In addition to that, the country is characterized by a very high number of networks in the field (Ruef and

Markard, 2010). The empirical field is relatively small and assessable: while 60 manufacturers, component suppliers and specific research institutes are organized in the major industry network (VDMA fuel cell working group), the wider fuel cell sector in Germany consists of around 100 manufacturers and component suppliers, as well as 60 specific research institutes. The business volume and number of employees are still quite low.[11]

To conclude, the TIS of stationary fuel cell in Germany can be said to be at the end of its formation phase, since important institutional structures and networks are established and the sector is currently moving towards commercialization and market preparation (Nygaard, 2008). However, the maturity phase, i.e. the formation of a sector with well-established markets and commercial products, has not yet been accomplished.

In addition three key factors have shaped our decision to examine this field. First, we could study the activities of innovating actors in the formation of the TIS in real-time, at a stage when the past innovation activities were still fresh and possible to study. Second, as we used a multiple case study design (Eisenhardt, 1989; Yin, 2009) we could compare different formal networks and system-building strategies in the same setting, and also better analyze how different strategies relate to each other in the process of TIS formation. Third, we were able to draw on the data of previous projects and reports (Markard and Truffer, 2008a; Musiolik and Markard, 2011; Ruef and Markard, 2010) which was helpful in delineating TIS boundaries and identifying key system builders in the field.

1.2.3 TIS boundaries and linkages

The emerging TIS on stationary fuel cells in Germany draws on a broad range of actors and competences from different fields (Brown et al., 2007; Markard and Truffer, 2008a; Nygaard, 2008). This explains why the TIS is partly constituted by actors, networks and institutions from (complementary) sectors, including the boiler industry, the electricity and gas supply sector and further complementary innovation systems, e.g. small-scale co-generation (cf. Figure 2).[12]

Fuel cell heating devices are manufactured in sequential steps and draw on a variety of competencies and pre-products. In technical terms, the fuel cell itself is accompanied by a fuel supply system and an energy management system, main functional elements which

[11] Source: VDMA fuel cell survey 2011 (c.f. http://www.vdma.org).

[12] In addition also fuel cell specific institutions, networks and actors have emerged in Germany in recent years including the National Innovation Program (NIP) Hydrogen and Fuel Cell Technology, a public-private partnership to support the development of a fuel cell industry, the National Organization Hydrogen and Fuel Cell Technologies (NOW GmbH), which organizes the implementation of the NIP, and the National Development Plan Hydrogen and Fuel cells (NEP), a fuel cell roadmap.

can be further differentiated in terms of sub-systems, components and materials. These parts of the final product are integrated and produced by different actor groups. On a general level, in an emergent fuel cell value chain we can differentiate between basic material suppliers, component suppliers, manufactures, end-users and service providers. (Hendry et al., 2007; Nygaard, 2008).

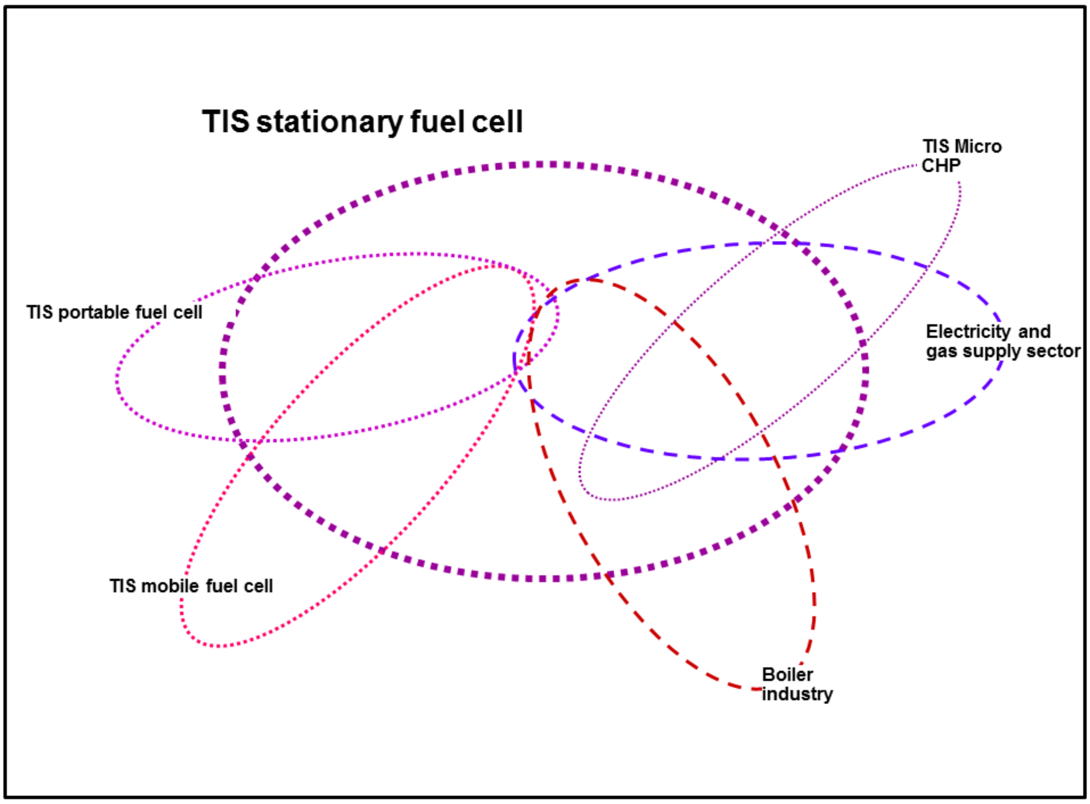

Figure 2: TIS of the stationary fuel cell and its coupling fields

Some major manufacturers in the German boiler industry, such as Vaillant or Baxi-Innotech, have decided to actively participate in the novel field and develop small-scale fuel cell heating devices. With their background in conventional heating devices, these firms contribute to the formulation of technical norms and play a strong role due to their established distribution channels (e.g. close contacts to local fitters). In other words, there is quite some overlap between the boiler industry and the emerging TIS on stationary fuel cells (cf. Figure 2). In the case of the core fuel cell components, however, these 'incumbents' had to co-operate with specialized fuel cell firms and research institutes, while additional specialized fuel cell manufacturers emerged and became active in Germany (e.g. Hexis from Switzerland and CFCL, an Australian-based fuel cell company).

In addition, many key suppliers from the automotive and chemical industry became active in the field of fuel cells, developing and producing core materials and components for mobile, stationary and portable applications. The technological requirements, fuel cell designs, key players and conditions of use are quite specific in each of these domains, which is why they will be regarded as three different technological innovation systems. While many material and component suppliers produce for all three areas of application, the TIS of stationary fuel cells interrelates with the respective TIS of mobile and portable fuel cells. Actors of these three domains also cooperate on a general level. A prominent example is the cooperation of actors from the different fuel cell applications in the development of the NIP fuel cell support program (see below).

In a similar vein, the TIS on stationary fuel cells is also linked to the electricity and gas supply sector, as most fuel-cell manufacturers closely cooperate with energy service providers in field tests, e.g. to commonly develop standards for grid connection and remote control and prepare end costumers and perform other kinds of market formation activities such as the education of service providers.

In this regard, fuel cells face similar challenges to other innovative and decentralized co-generation CHP technologies (e.g. internal combustion engines, stirling engines). The TIS on ‘micro CHP’ represents actors, innovation activities and institutional structures related to these other co-generation technologies. Again, there is a noticeable degree of overlap between the different fields and sectors. Players from the boiler industry as well as energy service providers are also active in micro CHP. Interestingly, actors in the fields of micro CHP and stationary fuel cells cooperate on specific issues (e.g. in the VDI network, see below), although the different technologies will compete with each other in the long term.

1.3 Thesis outline

The remainder of this thesis consists of 6 chapters. Chapters 2-5 were originally written in article format. Each of these chapters focuses on a set of specific research questions introduced above. While chapter 2 presents the theory, the following chapters 3-5 provide empirical results and methods used while underpinning the theoretical considerations developed in chapter 2. To increase the coherence of the thesis, ‘interludes’ between the chapters introduce the following chapter, and a concluding chapter summarizes the results and takes stock of an actor- and resources oriented analysis of TIS.

Chapter 2 introduces the underlying theory of the thesis. The TIS concept is combined with ideas from the field of strategic management. The chapter introduces the key concepts of resource based reasoning, and delineates strategically relevant resources beyond the organizational level. A framework is developed which distinguishes between resources at the organizational, network and system level. After identifying the limitations of current TIS studies with regard to actors’ strategies in system-building, the advantages of the delineated framework are discussed.

Chapter 3 introduces empirical results of a study of 5 key networks in the TIS on stationary fuel cells in Germany. In this chapter main actor, networks and institutions of the TIS selected are described. While reviewing the concept of networks used in TIS, the term of formal networks is introduced and used to analyze collective activities in system-building. Different types of network activities directed at the system level are identified and used to delineate different types of system resources.

Chapter 4 focuses on the interplay of resources at different levels. Again, the 5 key networks are empirically analyzed, this time concentrating on the abilities of the networks, rather than their output in terms of system resources as in chapter 3. The chapter presents the specific resource portfolios used by the networks, and introduces different types of resources actors in TIS can draw on while developing formal networks. The chapter concludes with a discussion of the characteristics of key networks for system-building, and shows how the interplay of different resources can be used for a resource-oriented analysis of TIS development.

In chapter 5, the developed framework of resources in TIS is used to generalize strategies (or modes) of system-building. Different cases and key actors are introduced, which are dedicated to building up the TIS of stationary fuel cells as well as their activities and strategies in system resource creation. Different system-building modes are delineated, and the chapter also discusses the strengths and weaknesses of these modes, and presents some insights into the nature of the deliberate system-building process.

Finally, chapter 6 provides answers to the research questions raised above, summarizing both the major results of the thesis and the theoretical contributions to TIS literature in structural as well as dynamic terms. The thesis concludes with a consideration of future prospects and some general questions for further research.

Interlude chapter 2

Institutional structures in emerging technological fields are strategically shaped by organizational actors. In this conceptual chapter we develop a framework to explain the strategies of organizations in emerging fields. Towards this end, we combine the technological innovation systems approach with resource-based reasoning in the strategic management literature. More specifically, we define and compare resources at the organizational, network and system level and highlight the strategic relevance of collective resources beyond the firm level. Our argument is threefold: First, a technological innovation system can be viewed as a set of collective resources, which provide positive externalities for the actors in the field. These system resources are continuously (re-) created and transformed. Second, organizational actors play different roles in this process, based on the organizational resources they control and the strategies they pursue. Some actors may be more important than others, or even non-substitutable. Third, the formation of system resources may be highly context-dependent, which means that there are limitations for the imitability and transferability of successful innovation systems.

2 Innovation systems and resource-based reasoning: Explaining strategic action in emerging technological fields

2.1 Introduction

The emergence of new technologies and related organizational fields strongly depends on the strategic action and interplay of various kinds of actors (e.g. Garud and Karnoe, 2003; Van de Ven et al., 1999). Through this interplay, existing institutional structures change and new ones develop as the technology matures. Examples of such structural elements include technological standards (Funk and Methe, 2001; Tassey, 2000), practice tests to determine the value of a novel technology (Kaplan and Murray, forthcoming; Rao, 1994), collective expectations and cognitive frames (Borup et al., 2006; van Lente and Rip, 1998a), specific regulations or public R&D funding schemes (Jacobsson and Johnson, 2000; Nelson, 1993). These elements are often supportive, e.g. as they coordinate the activities of different firms, but they may also constrain action. They are part of a broader institutional structure that shapes the direction of technology development and is often essential for the take-off of novel technologies (Jacobsson and Johnson, 2000; Nelson and Nelson, 2002; Smith, 1997; Van de Ven et al., 1999; Van de Ven, 2005).

Due to their importance, the aforementioned elements may be in the focus of the strategic activities of innovating actors. For example, firms, associations, public authorities and other actors shape standards and technical guidelines (e.g. Garud et al., 2002), try to build common visions and expectations (e.g. van Lente and Rip, 1998b), or lobby for public support or specific regulations (e.g. Oliver and Holzinger, 2008). Through these kinds of activities, organizations co-create the technological field, or system, they are operating in. From a strategic perspective, it may be argued that they develop resources at the level of the field that can be used collectively.

While the innovation literature acknowledges the essential role of firms and other actors in such processes of field formation (e.g. Bergek et al., 2008a; Carlsson and Stankiewicz, 1991; Garud and Karnoe, 2003; Jacobsson and Johnson, 2000; Van de Ven, 2005), it is rather silent about what drives innovators to commit to the creation of supportive institutional structures. With this conceptual chapter we therefore take a closer look at the strategic relevance of institutional structures, or collective resources, in emerging technological fields. We explore why organizations deliberately contribute to creating and shaping such resources.

A reference and starting point for our argument is the systems of innovation perspective, which highlights the dynamic interplay of organizations and broader institutional structures in technological fields (cf. Carlsson and Stankiewicz, 1991; Carlsson et al., 2002b; Edquist, 2005). The general idea of this framework is to identify regularities in the emergence of innovative technologies in order to clarify the conditions under which they develop quickly and become a success or fail (e.g. Bergek et al., 2008a; Hekkert et al., 2007; Markard and Truffer, 2008b).

To address the strategic relevance of institutional structures for organizations, we draw on resource-based reasoning and the corresponding strategic management literature (e.g. Barney, 1991; Barney, 2001b; Dierickx and Cool, 1989; Kraaijenbrink et al., 2010; Priem and Butler, 2001a). The resource-based view relies on two key assumptions: Organizations control different resources and these differences may persist over time as some resources are difficult to transfer between organizations or even immobile (Barney, 1991; Dierickx and Cool, 1989). While the approach has received broad attention in the field of management studies, it has also been criticized, especially with regard to whether it can formulate generalizable conditions for sustained competitive advantage (cf. Barney, 2001a; Kraaijenbrink et al., 2010; Priem and Butler, 2001a). In our analysis, explanation of competitive advantage is not the primary issue. We also apply a more context-specific perspective on the value of resources (cf. Kraaijenbrink et al., 2010).

The argument which we elaborate in the following is threefold. First, strategically relevant resources do not just exist at the level of organizations but also beyond (e.g. Dyer and Singh, 1998; Foss and Eriksen, 1995; Gulati, 1999). A technological innovation system can be viewed as a set of collective resources, which provide positive externalities and which are continuously (re-)created and transformed by the actors in the field. System resources are non-excludable, i.e. they can be accessed by a larger number of actors. Despite the collective nature of these resources, firms may have strategic reasons to shape and develop them.

Second, in a technological field, actors play different roles based on the organizational resources they control and the strategies they pursue. As a consequence, some actors may be more important than others in the field and for the development of collective structures. Of particular importance are actors which control resources that are critical for the field. Third, the formation of system resources may be highly context-dependent, which explains why we may observe limitations of the transferability of successful innovation systems (in regional or technological/sectoral terms).

The chapter is structured as follows. Section 2.2 introduces the TIS literature and section 2.3 reviews key concepts of resource-based reasoning. Section 2.4 then presents the conceptual transfer from organizational resources to collective resources at the network and system level. This is followed in section 2.5 by a discussion of the strategic relevance of these different kinds of resources. Section 2.6 addresses our key question about the reasons for strategic action towards the formation of collective resources and section 2.7 concludes discussing the implications of our framework for innovation studies.

2.2 Technological innovation systems and the need to explain actor strategies

The technological innovation systems framework has been developed to study the emergence and development of new technologies over time and to identify general mechanisms or interdependencies that explain specific courses of development (e.g. Bergek et al., 2008a; Carlsson et al., 2002b; Jacobsson and Johnson, 2000; Markard and Truffer, 2008b). The framework is part of a broader family of innovation system approaches including national, regional or sectoral innovation system perspectives (see e.g. Carlsson, 2007; Chang and Chen, 2004; or Edquist, 1997 for an overview). The TIS approach originated from research on technological systems where the focus was not so much on the *emergence* of new technologies but on the performance of established systems and their contribution to economic growth, for example (Carlsson and Stankiewicz, 1991; Carlsson, 1995). The framework highlights the influence of institutions on innovation processes and the importance of actors collaborating in larger networks that exchange knowledge and facilitate the use of complementary resources. It also acknowledges phenomena such as coupled dynamics, cumulative effects, path dependency and potential technological lock-in. A *technological innovation system* (TIS) can be defined as

> "... a network of agents interacting in the economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion and utilization of new technology." (Carlsson and Stankiewicz, 1991, 94).

Actors are individuals but also - and most importantly - organizations such as private firms or firm sub-units, governmental and non-governmental agencies, universities, research institutes, associations etc. Institutions can be conceived of as rules that influence the activities and decisions of the actors.[13] They set incentives for actors to do certain things and to avoid others. Institutions include norms, laws, regulations, guidelines, contracts, values, culture, cognitive frames etc. Institutions can be interpreted as the rules of the game, while actors, or organizations, are the players (e.g. Edquist, 2005; North, 1990). Organizations can act in the sense that they formulate aims and pursue deliberate strategies to reach these aims, while institutions cannot. In a way, institutions are passive as they cannot deliberately transform themselves like actors. Instead, they evolve and

[13] Note that different definitions for institutions have been proposed in innovation studies as well as in economics or the social sciences (see e.g. Hollingsworth, 2000 for an overview). The interpretation of institutions as rules is a rather simplified concept.

change as a result of the effects of other institutions and of the activities of organizations.[14]

The relationships among the system components, i.e. among as well as between actors and institutions, are manifold. Actors may compete but also collaborate with each other or they may perform transactions, i.e. trade goods, services or knowledge. Institutions may support each other but they may also be in conflict (Edquist, 2005). Moreover, they may exhibit a certain hierarchy in their structural set up.

Organizations and other actors are the major source of agency in the TIS framework. Many empirical TIS analyses, especially narratives on technology development, therefore refer to the role particular actors or actor groups have played, e.g. as they set up pilot projects, developed particular technological designs, implemented common standards or lobbied for favorable regulatory conditions (e.g. Bergek and Jacobsson, 2003); Jacobsson et al., 2004; Negro and Hekkert, 2008). Some studies also point to so-called prime movers, actors who are "...technically, financially and/or politically so powerful that they can initiate or strongly contribute to the development and diffusion of a new technology." (Jacobsson and Johnson, 2000, 630). The TIS framework, in other words, accounts for actors creating and shaping institutional structures (and TIS functions) as well as for these structures having an impact on the strategic decisions of actors. Furthermore, it is acknowledged that organizations play different roles, e.g. as they exhibit different levels of economic competence (Carlsson and Stankiewicz, 1991; Jacobsson and Johnson, 2000).

However, what is missing in our view is an explicit model that explains the strategic moves of organizations and the differences among actors. Take, for example, firm entry into a TIS, i.e. the decision of an organization to become active in the novel technological field: within the TIS framework, studies refer to and highlight institutional structures at the system level (or beyond) that stimulate entry (e.g. Negro et al., 2007; Negro et al., 2008). However, the framework does explain why some organizations enter earlier than others or whether some system structures are particularly important for a certain type of firms.

Another crucial phenomenon in emerging technological fields is the collaboration of different actors in creating broader support structures and initiating institutional change. When lobby networks of innovators, for example, succeed to convince policy makers to set up a technology-specific R&D program, we would like to understand why firms jointly collaborated here despite the risk that others do not and take the opportunity for free-riding. With the current framework we have difficulties to understand the conditions under which organizations commit themselves to developing such collective structures and whether it matters who comes together in these processes.

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[14] Cf. the notion of institutional entrepreneurs or institutional actors in this regard (e.g. Beckert 1999; DiMaggio 1988). Edquist and Johnson (1997) have described the relationship between institutions and organizations as a dual subject-object relationship.

An even more general question is why some actors are more important for the development of a technological field than others as the concept of prime movers suggests (see above). Why do some firms play a particularly strong role in the system and why may it be difficult for others to imitate or substitute this role? The framework we elaborate below can provide a basis for exploring these actor related issues in further detail. In the article, however, we concentrate on the question why some firms might contribute to creating and shaping supportive institutional structures in emerging technological fields.

2.3 Resource-based reasoning and key concepts at the organizational level

Resource-based reasoning can be traced back to the contributions of Penrose (1959), Wernerfelt (1984), Rumelt (1984) or Teece (1984) and has received increasing attention from the early 1990s on. Today, the resource-based view (RBV) has become a very influential framework in the strategic management literature (Lockett et al., 2009; Kraaijenbrink et al., 2010) and it has been complemented by related concepts such as core competences (e.g. Prahalad and Hamel, 1990), dynamic capabilities (e.g. Teece et al., 1997) and the relational view (e.g. Dyer and Singh, 1998). The goal of the resource-based view is to explain why organizations are able to achieve a sustained competitive advantage (e.g. Barney, 1991). Resource-based reasoning focuses on the influence of elements and processes within the firm and thus contrasts, for example, with the positioning view that assigns industry structure and the firm's position in the industry the key role for explaining competitive advantage.

A core idea of resource-based approaches[15] is that not all factors or assets which are of strategic importance to firms can be traded in markets (e.g. Dierickx and Cool, 1989;). Firm reputation, customer loyalty, organizational culture, highly motivated teams or technological know-how are examples of assets that are difficult or impossible to trade or transfer from one organizational context to another. In order to use such assets, a firm has to develop and/or accumulate them over time. Resource-based reasoning also points to the difficulties to imitate particular resources, e.g. due to time compression diseconomies, asset stock interconnectedness, unique historical conditions or causal ambiguity (Dierickx and Cool, 1989; Barney, 1991). For the purpose of this paper, we especially draw on these core arguments, e.g. in order to explain why firms different roles in emerging technological fields and why some organizations may be more important than others.

The resource-based view has also been criticized for a number of reasons (cf. Kraaijenbrink et al., 2010; Priem and Butler, 2001a). Among these is its assumption that the value of resources is given or exogenously determined by the market a firm is

[15] When referring to resource-oriented approaches or resource-based reasoning in the following, we think of the commonalities in the above mentioned streams of literature and not just of the RBV in a more narrow sense.

operating in (Kraaijenbrink et al., 2010). As a consequence, the RBV leaves little room for a more subjective view that acknowledges the role of actors in imagining and actively creating resource value. It is especially in dynamic environments, where the latter perspective is important. Another major critique relates to the overly inclusive definitions of resources that prevail in some of the core contributions to the literature (see e.g. Priem and Butler, 2001a and Barney, 2001a for a discussion). Ambiguous definitions did not only evoke the tautology critique but also hampered theory development (cf. Kraaijenbrink et al., 2010).

Against this background, clarification is needed of how we will use the key concepts in the following. A major distinction we make is between objects or inputs (assets, resources), processes that work on these inputs (routines, strategic decisions) and attributes of an organization (capabilities).

2.3.1 Organizational resources

We conceptualize resources as assets that are of strategic relevance to an organization. We use the notion of assets in order to distinguish resources from processes (or organizational routines) that make use of these assets and may also change them. Resources can be inputs for processes and they also can be the outcome of processes. Resources can even guide or structure processes, but we do not regard them as a source of agency although they affect the strategic decisions of organizations. We also distinguish resources from capabilities (cf. Amit and Schoemaker, 1993). Furthermore, we assume that the strategic value of resources is context-specific, i.e. it depends on the specific environment an organization is operating in (and even more so if this environment is dynamic) and also on strategic moves which actively create and change resource value (Kraaijenbrink et al., 2010). Organizational resources are typically controlled by a specific organization although limitations may apply (ibid.).

These specifications still leave us with a broad spectrum of potential resources. Within this spectrum, immaterial and even inexhaustible assets which - over time - are generated or accumulated by an organization might deserve particular attention (cf. Dierickx and Cool, 1989). Take for example organizational quality standards or culture, which emerge from the interplay of individuals and/or teams within the organization. Or take the reputation of a firm, which is shaped over time through the activities the firm performs in relation to other actors in its environment. Such kinds of assets are *emergent properties* of an organization that have developed and changed over time and continue to do so. They represent the aggregated outcome of complex processes at the firm-level and beyond. They have in common that they are inseparably tied to the firm.[16]

[16] From a formal point of view, they are either *attributes,* i.e. characteristics of the organization that cannot exist without the object they relate to or *constructs* that have been defined in a way that they are inseparable of the object they relate to. Other assets, in contrast, do not need another

On the basis of these considerations we propose the following definition:

> Organizational resources are tangible and intangible assets of strategic value that are owned or controlled by an organization. Of particular interest are those intangible assets that are generated and accumulated by the organization in a way that they have become inseparable and thus unique. Potential examples of organizational resources are employees, technological know-how, production facilities, patents and licenses, contracts, brands, access to natural resources, reputation, organizational culture, internal quality standards or customer contacts.

Note that whether and where organizational resources are used depends on strategic decisions, i.e. they may just be deployed at a certain time or to a specific business field. Moreover, a change in strategy typically leads to a re-evaluation of the strategic relevance of the organizational assets (or resources).

2.3.2 Organizational capabilities and routines

Like resources, organizational capabilities have been defined and used differently in the management literature (e.g. Wang and Ahmed, 2007). Following Amit & Schoemaker (1993) and Grant (2008), we interpret capability as the capacity of an actor to deploy resources for a desired goal. However, unlike Amit & Schoemaker (1993), we distinguish between capabilities and processes. In our interpretation, capabilities depend on processes (and resources) but are no processes themselves. Rather they are attributes of an actor and thus - by definition - inseparable from the object they relate to. Furthermore, we leave room for strategic decisions, which means that the capabilities of an organization affect her leeway for strategic decision making but whether, where and how these capabilities are actually is not fully determined. In other words, capabilities represent the *potential* of an organization to achieve a particular end.

> Organizational capability (skills or competence) is the ability of an organization to do something and to achieve specific ends on the basis of a particular combination of assets, resources, processes and routines.

Competences and capabilities are typically applicable to different products or business fields in multi-business firms. This holds in particular for core competences, which relate to the key business of a firm (e.g. Prahalad and Hamel, 1990; Teece et al., 1997).

As a particular sub-set of capabilities, dynamic capabilities have received quite some attention recently as they represent the capacity of an organization to develop, adapt and re-configure resources in order be successful in rapidly changing environments (e.g. Ambrosini and Bowman, 2009).

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object to exist and they can - at least principally - be transferred to other organizations. Examples of the latter include natural resources, human resources, codified knowledge or financial capital.

> Dynamic capability is the ability of an organization to regularly and efficiently re-configure resources and routines (and thus to adapt ordinary capabilities) in order to cope with rapidly changing market environments.

Note that with this definition we deviate from the understanding of dynamic capabilities as processes or routines (e.g. Eisenhardt and Martin, 2000; Zollo and Winter, 2002). Still, we follow the prevailing understanding in the literature that dynamic capabilities are a particular type of capabilities as they are inward oriented with the aim to reconfigure resources and routines and thus to change or adapt ordinary capabilities in the end.

The concept of organizational routines has gained a lot of attention in empirical and conceptual work, which was largely due the central role it was assigned in evolutionary economic theorizing. Nelson and Winter (1982) defined routine as *"... a repetitive pattern of activity in an entire organization ..."* (p.97). A more recent, but very similar definition is the following: *"... organizational routines ... refer to ... regular and predictable patterns of activity made up of a sequence of coordinated actions by individuals."* (Grant, 2008, 137)

Still, many different understandings and definitions exist and three major sources of ambiguity can be identified (Becker, 2004). These include the distinction between recurrent activities at the individual and the collective level, the difference between routines as cognitive rules or patterns of behavior and the issue of whether actors have an alert, performative role when executing routines or not. With regard to the first aspect, we will limit the notion of (organizational) routines to the collective level, while recurrent patterns of individuals are called *habits* (Becker, 2004; Dosi et al., 2000). As to the second controversy, we suggest regarding routines as processes or activities, not as cognitive regularities or institutions (see below). And with regard to the third issue, we believe that actors should be assigned a certain degree of freedom of not to (fully) comply with routines, i.e. they can interpret and change them, although this is the exception rather than the rule.

> Organizational routines are regular patterns of activity at the organizational level. They are executed by employees (individuals) or groups of employees with a certain but limited degree of freedom.

To summarize, resources can be thought of as elements (what an organization owns or has access to), while capabilities represent a potential, i.e. what an organization can do, and routines are processes (what an organization regularly does). These elements are in each specific organization complemented by the strategic goals it wants to achieve (e.g. Mintzberg, 1987). In other words, most situations are characterized by discretion, or strategic leeway. Whether specific resources and capabilities, for example, are applied in a new business field does not just depend on how well they are suited for that but also on the more general strategic goals a firm pursues.

Having discussed and defined these core elements at the organizational level, we will now elaborate on the concept of resources at higher levels of aggregation.

2.4 Resources at higher levels of aggregation

While organizational resources are certainly in the focus of the management literature, the resource concept has also been transferred to higher levels of aggregation including inter-firm networks (Gulati, 1999; Lavie, 2006) and industries (Foss and Eriksen, 1995). In fact, the environment of a firm can be thought of as "a large external resources and capabilities space" (Foss and Eriksen, 1995, 45). The core idea, on which we will elaborate here, is that there are assets beyond the organizational level of that can be of strategic value for firms. Examples include common standards (Funk and Methe, 2001), industry associations and lobbyists (Foss and Eriksen, 1995), specific regulations (Jacobsson and Johnson, 2000), collective technology-related expectations (van Lente and Rip, 1998a), trust among different actors (Barney and Hansen, 1994) or a common culture firms share (Dyer and Singh, 1999). Such kinds of assets are particularly important for emerging technological fields, e.g. in order to facilitate knowledge creation or to guide search processes (Van de Ven et al., 1999).

In the following, we will first take a closer look at (formal) networks and resources at the network level. Networks of innovators have been identified to play a key role for the development of new technologies (e.g. deBresson and Amesse, 1991; Jacobsson and Johnson, 2000; Pyka and Küppers, 2002). Then we turn to the innovation system level, where we define so-called system resources. A conceptual comparison of organizational, network and system resources concludes this section.

2.4.1 Networks and network resources

Organizations often cooperate in networks or inter-firm alliances. From a resource perspective, a key reason to do so is getting access to organizational resources owned by a cooperation partner (Das and Teng, 2000; Lavie, 2006). Through such kind of strategic cooperation, a firm can use resources without the need to first acquire, transfer or develop them. This is particularly useful for resources that are not available through market exchange or otherwise (Das and Teng, 2000). The study of firms cooperating in networks has extended resource-based reasoning to resources that are located outside of the boundaries of the focal organization (e.g. Das and Teng, 2000; Dyer and Singh, 1998; Lavie, 2006). The condition that resources have to be *owned* or *controlled* by a firm in order to become a source for competitive advantage is relaxed. Instead it is argued that *access* to resources (controlled by somebody else) can be sufficient (Lavie, 2006). In the so-called relational view, even the analytical focus shifts from single firms to inter-firm networks (Dyer and Singh, 1998).[17]

[17] This shift has even been interpreted as a new and very distinct path of explanation because it leads to different management recommendations than the RBV with its firm focus (Duschek, 2004).

It has remained an issue for debate though, where the sources of relational rents are located and how to define network resources (Lavie, 2008). Lavie (2008) suggests concentrating on "…assets that are owned by the firm's partners but can potentially be accessed by the firm through its ties to these partners…" (p. 548).[18] These include for example the reputation of a partner or its technological capabilities made accessible through the partnership (Lavie, 2006). In this perspective (Lavie, 2006, 2008), resources are always located at the level of organizations, i.e. they are either owned by the firm in the focus or by a partner firm.

Gulati (1999), in contrast, argues that "Network resources inhere not so much within the firm but in the inter-firm networks in which firms are located. ...firm network resources result from the informational advantages they obtain from their participation in inter-firm networks that channel valuable information." (p. 399). Similarly, Dyer and Singh (1998) maintain that "…a firm's critical resources may extend beyond firm boundaries…" (p. 660). This approach (Dyer and Singh, 1998; Gulati, 1999) acknowledges that strategically relevant resources might be located *beyond organizational boundaries*.[19]

For our purpose, we adopt the latter perspective: Apart from organizational resources, we conceptualize and study *resources which are not owned by any organization*, e.g. as they emerge at the network or innovation system level. Dyer and Singh (1998, 1999), for instance, refer to the institutional environment in Japan as a source of competitive advantage: it fosters trust among cooperating partners and controls opportunism. Common governance structures in formal networks, a common culture, collective expectations or shared visions may provide comparable benefits. The essential issue here is that these collective assets may be of high strategic value for some or all firms that have access to them. We will return to this in section 2.5.

Through cooperation in a network, firms thus not only get access to organizational resources controlled by their partners but also benefit from resources that emerge through the interplay of actors in the network. In contrast to the former, the latter type of resources would not exist if firms were not interacting and cooperating in a specific way. These network resources, moreover, are typically not available right from the beginning but they develop (and change) over time. Before we can turn to our definition of network resources, we have to clarify our understanding of networks.

Two general types of networks can be distinguished. Networks may have been deliberately established for strategic reasons (alliances, joint-ventures, lobby initiatives), or they may have emerged in a less purposive way, e.g. through the "natural" interaction

[18] He also argues that it is important to distinguish the resources themselves from the ability to obtain them.

[19] Still Gulati's (1999) conceptualization of network resources remains narrow with its focus on informational advantages through a firm's embeddedness in different networks.

of organizations in a specific regional context (cf. Molina, 1999). The first type can also be referred to as formal networks whereas the latter are informal networks related to the broader social context firms are embedded in. In our framework, we concentrate on formal networks, which have a clearly defined set of members working together towards common goals. We define *network resources* as follows:

> Network resources are non-excludable assets within a formal network that are of strategic value for network members (e.g. in comparison to non-members). Their strategic value may be different for different members. Network resources are generated (intentionally or not) through the interplay of actors in the network. Network resources cannot exist without the network.

Examples of network resources are network culture, trust among members, a shared network mission, common goals, a specific mode of network governance or the reputation and power of a network.

2.4.2 System resources

As resources emerge through the interplay of actors we expect them not only at the level of formal innovation networks but also elsewhere, e.g. at the system or industry level. Services provided by industry trade organizations, for example, have been labeled as industry resources as they are accessible by a broad range of actors within an industry (Foss and Eriksen, 1995). Similarly, the reputation of a novel technology (Rao, 1994), tests that determine value of a novel product (Kaplan and Murray, forthcoming) or common expectations in a field (Konrad, 2006) can be interpreted as collective resources of an emerging technological field.

Similarly to the definition of network resources, we introduce the notion of system resources as assets which are tightly related to a specific technology and which are strategically relevant for innovating actors in the field.

> System resources are non-excludable assets that are of strategic value for actors involved in the development of the new technology (system 'members'). System resources are generated (intentionally or not) through the interplay of actors in a technological innovation system. Their strategic value may be different for different actors. System resources are technology specific and tightly linked with the corresponding innovation system.

Examples include technological standards, professional norms, technology specific collective expectations, shared heuristics as well as specific regulations supporting the focal technology. Note that system resources are more difficult to determine than resources of formal networks, because system boundaries are not as clear-cut as the boundaries of formal networks. In fact, system boundaries co-develop with system resources (see below). The notion of system resources has been introduced because (technological) innovation systems are an established unit of analysis in the innovation literature. In conceptual terms, we refer here to collective resources for which no formal access rules exist. In this regard, system resources are comparable to industry resources or resources that emerge in informal networks.

2.4.3 Conceptual comparison and examples of resources at different levels

Resources at the organizational, network and system level differ in several respects. In the following, we take a closer look at the conditions for resource access and the differences in terms of resource formation (cf. Table 1). With regard to the latter it will be compared how and where (i.e. at what level of aggregation) resources are developed.

Table 1: Conceptual comparison of resources at different levels of aggregation

Type	Characteristics of resource access	How are resources created?	Where are resources created?	Examples
Organizational resources	Exclusive, resource access controlled by the organization	Resources are acquired, strategically created or emerge.	Organizational level	Reputation / legitimacy (Aldrich and Fiol, 1994) Organizational culture (Barney, 1986a) Technological expertise
Network resources	Non-excludable within the network, access regulated through network membership rules	Transfer from members to network, strategic creation by network members, emergence through interplay of network members	Formal network level and also organizational level	Trust among network members (Barney and Hansen, 1994) Shared goals Governance mechanisms (Dyer and Singh, 1998) Network culture
System resources	Non-excludable, open access	Resources are strategically created by specific actors / actor constellations or emerge through interplay of actors in the system.	System level, formal and informal network level, eventually organizational level	collective expectations (Borup et al., 2006) technology-specific standards (Funk and Methe, 2001) specific regulation tests to create legitimation (Rao, 2002) political commitment in favor of a specific technology (Walker, 2000)

Source: own depiction

Access to organizational resources is typically controlled by a single organization. This organization can decide to use the resources exclusively or to grant other firms, e.g. partners in a strategic alliance, access to some selected organizational resources (Lavie, 2006). Network and system resources, in contrast, are collective resources, i.e. several organizations use them together and excludability is limited. In formal networks, membership and resource access are regulated explicitly, e.g. by membership rules. Network resources have the character of 'club-resources', i.e. network members (insiders) have access to these resources while outsiders do not. At the system level, such formal regulations do not exist and access to system resources is open to all firms, cf. Table 1. This does not imply, however, that all firms can equally reap the potential benefits of system resources. We will come back to that in the next section in which we discuss the strategic relevance of different kinds of resources.

Differences between the three types of resources also exist with regard to resource formation. As a general rule, organizational resources are formed at the firm level, network resources are formed in networks and system resources at the system level. However, there are at least two exceptions here. First, while some resources (at whatever level) are *created* through purposive strategic action, other resources *emerge*, i.e. they evolve in a less controlled way through the interplay of actors. Examples for the latter include firm culture (Barney, 1986a), trust among network members, de facto standards or collective expectations (Borup et al., 2006). Note that this does not imply that emergent resources cannot be strategically influenced to some extent. This may in fact be the case (van Lente and Rip, 1998b). The point is that the formation of emergent resources is a process that is neither fully controllable nor easily replicable. As a consequence, we can expect such resources to be very specific according to the context in which they developed.[20] Moreover, they are difficult to imitate or transfer.

Second, resources are not exclusively created at a specific level. System resources such as technological standards, for example, may be developed in formal networks or committees (Funk and Methe, 2001), which means that some actors are actively involved in the creation process while a broader range of actors subsequently has access to the resource.[21] Similarly, system resources may strongly be influenced by single organizations as was the case with Java technology and the dominant role of Sun Microsystems in the standard creation process (Garud et al., 2002). Also public authorities can play a prominent role in the provision of system resources. Take for example the strong role of governments in pushing nuclear energy technology, e.g. through supportive regulations, intergovernmental contracts or R&D support (Kaijser, 1992; Walker, 2000). For the formation of network resources similar reasoning applies. Network governance rules, for instance, are typically developed over time through interaction and negotiation of

[20] See also Foss and Eriksen (1995) in this regard: "… industry capabilities emerge in a historical process from the interaction of multiple firms within industries." (p. 48)

[21] Note that standards entail benefits for some actors and compliance costs for others. The notions of resource and resource access have to be interpreted against this background.

the different network members but they may also be controlled, or significantly shaped, by a single member.

In Figure 3 we have arranged organizational, network and system resources in a systematic way to distinguish at what level resources are formed and who has access to them. Note that the examples given in brackets are just illustrations for a specific type of resource. This does not imply that e.g. network governance rules are only or typically created by a single organization.

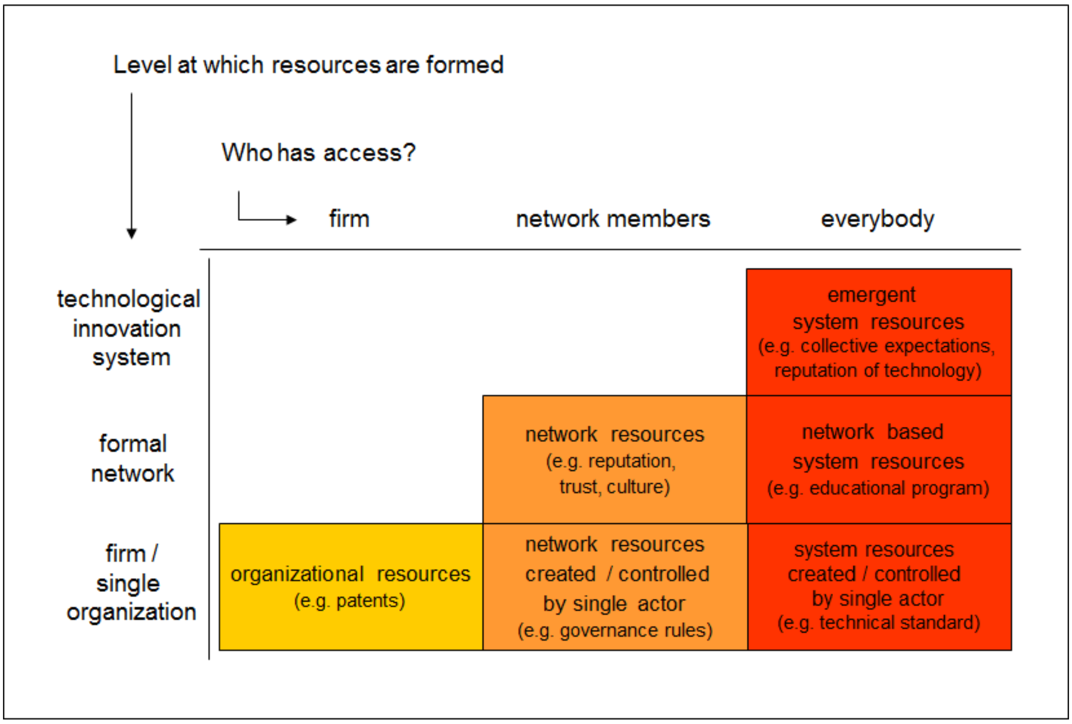

Figure 3: Differentiation of resources according to where they are formed and who has access to them

2.5 Strategic relevance of network and system resources

In this section we take a closer look at the strategic relevance of different kinds of resources to later explain some of the strategic moves of firms in emerging technological fields. We define strategic relevance as the contribution (of a resource) to achieving the strategic goals of a firm.

The strategic relevance of resources depends on several factors. If resources are rare or even unique (in a certain market), difficult to imitate and non-substitutable they may become sources of competitive advantage for a firm (Barney, 1991). In this argument resource characteristics are in the focus and it is assumed that these characteristics determine the strategic relevance of a resource. Recent contributions to the RBV literature, however, have highlighted that the issue may be more complex because the interplay of different resources as well as the context in which they are applied also plays a role (Kraaijenbrink et al., 2010; Makadok and Coff, 2002).

In our framework, another conceptual extension is made. The aforementioned arguments are based on the assumption that an organization can use resources exclusively. For network and system resources, however, this assumption does not hold true because a broader set of firms has access to these resources (cf. Table 1). For example a technological standard that lowers uncertainty and transaction costs for a group of firms in a specific field is of little or no strategic relevance for competition among these firms, no matter whether the standard is unique or difficult to imitate. It may well be relevant though in situations where these firms compete with others that develop a technological alternative (perhaps under a different standard). The strategic relevance of resources therefore also depends on which competitive relationship we are looking at.

Furthermore, the strategic relevance of resources is affected by firm related characteristics. Complementarity of resources is certainly a crucial issue here (e.g. Das and Teng, 2000; Makadok and Coff, 2002). The strategic relevance of a resource increases if it is well complementary with the existing resources a firm controls. Take for example a system resource in the form of a technology specific public research program. For a research oriented upstream technology developer such a program may represent a relevant resource that complements in-house R&D, while a downstream service provider in the same technological field can eventually make little use of this system resource. Similar reasoning applies in the case of technological standards. If the product variant a firm develops is highly compatible with a specific technological standard in the field, this standard will represent a strategically relevant system resource for the firm because it increases the value of the organizational resources its product is based on. For other firms, however, the same standard may even represent a burden as it devaluates their organizational resources.[22] Similar arguments can be made with regard to whether a firm has a potential substitute for a system resource at its disposal or whether it is able to imitate the system resource. If this is the case, the strategic relevance of the system resource decreases for the specific firm and vice versa. Note that with this interpretation collective resources have no objective relevance but their strategic value depends on the eye of the beholder, i.e. on the firm that is using them and the situation it is used in. A crucial point behind all these arguments is the basic assumption of resource-based reasoning that firms are different (as they control different resources) and that these differences persist, at least to a certain extent. Under these circumstances, the benefits (or burdens) that collective resources offer for different firms vary. In a simplified model, we can think of each collective resource as being characterized by a gravity field, which attracts some firms, i.e. those that realize a benefit from the collective resource, and repels others (for which the resource represents a burden).

[22] Such burdensome resources affect strategic goals negatively (negative relevance).

Table 2: Extension of characteristics that influence the strategic relevance of resources

Type	Organizational resources	Network resources	System resources
Access	*Restricted / exclusive*	*Semi-exclusive*	*Open*
Resource related characteristics (Barney, 1991)	Important	Important	Of some importance
Firm / context related characteristics (Kraaijenbrink et al., 2010; Makadok & Coff, 2002)	Of some importance	Important	Important System resources may be more or less demanding (specific) in terms of complementary organizational resources
Competitive relationship	Of little importance (equal for most kinds of competitive relationships)	Important (Competition between network members and non-members)	Important (Competition between firms with complementary resources and those without)

Source: own depiction

2.5.1 Technological innovation system as a set of evolving collective resources

In a technological innovation system, many of these resources exist with partly overlapping constituencies of innovating actors. In fact, we can understand such a system as an area, in which many of these 'resource fields' overlap and a certain density of attraction (and repulsion) occurs as a consequence. Innovation system boundaries are then shaped by the collective resources emerging and changing in a specific technological area. A broader field may also be characterized by competing technological systems (e.g. related to competing technological designs) with different constituencies that strategically shape and further 'their' system resources, and eventually also hamper those resources that support the competing design(s).

Note that the fields that surround collective resources may also be shaped by formal access rules, especially in the case of network resources. As a consequence, competitive relationships in an emerging innovation system are shaped by the characteristics of collective resources, by firm characteristics and by resource access rules. As these are not pre-defined or given at the outset, the development of a technology, i.e. which kinds of markets emerge, what dominant designs are, which firms compete, or how the value chain looks like, is tightly connected with the formation of collective resources and access rules.

Such arguments are part of the bigger picture of the dynamics in emerging fields. Resource characteristics (e.g. its potential range of complementarity) as well as access rules develop and change over time due to the interaction, negotiation and strategic maneuvers of different actors. Changing resource characteristics, again, have an impact on the competitive relationships and on the boundaries of technological fields. We expect that such dynamics are particularly pronounced in emerging technological innovation systems with product designs, business models and actor networks in flux. In this chapterwe cannot address the underlying dynamics in every detail. Yet, we can take a closer look at the rationales for resource creation as a first step in this direction.

2.6 Strategic reasons to create collective resources

The conceptual model developed above can be used to explain the strategic moves of actors. It is based on the general assumption that firms develop and expand their resource base in a way, in which they expect to fare better than competitors. Firms have different strategic options to shape the resource base they can draw upon. First, they can acquire or develop organizational resources, which they use exclusively. Secondly, they can form alliances to get access to organizational resources of other actors. Another reason to set up or enter into such formal networks is to commonly develop and exploit network resources. Thirdly, firms can also decide to contribute to the creation of system resources and to actively shape the emerging field.

It was already argued that various competitive relationships may exist for a firm. As a consequence, we expect firms to pursue different strategies to address the possibly differing needs of these relationships. As we cannot explore all these strategic options in detail, we concentrate on the rationales for creating and shaping collective resources in the following. These are particularly interesting for the study of emerging technological fields. Through strategies that are directed at developing and shaping system resources, actors contribute to the formation of the field (and the technology). As we understand the conditions under which firms become ‘system entrepreneurs’, we will eventually be able to explain system performance with reference to the strategic moves of the actors in the field.

A key question in this regard is why firms contribute to the development of resources at the system level although they cannot benefit exclusively from these resources (King and Lenox, 2000). In general, system resources provide benefits as they spur the development of the specific technology (Foss and Eriksen, 1995; Van de Ven, 2005). Firms with resources that are well complementary with the new technology therefore have a general incentive for system resource creation vis-à-vis competitors that do not have such complementary resources. However, there might be several firms with such complementary resources which means that we might face a classical collective action dilemma here: in an attempt to free riding, each firm may wait for others to move first and commit to system creation.

However, there are several reasons why collective resources are created despite potential free riding. Let us first argue on the basis of costs and benefits, assuming that these are known before making a decision. Firms with different organizational resources may face different costs when contributing to the creation of system resources. The effort to create a common standard, for example, may be significantly lower for firms with a well-known reputation in a specific field. Similarly, firms can also be expected to reap the potential benefits of system resources to a different degree (see above). Large incumbent companies, for example, may internalize so much of the benefits of the positive reputation of an industry that they take a lead in the development of voluntary standards that maintain this reputation (King and Lenox, 2000; Olson, 1965). Firms that expect low costs and high benefits are therefore more likely to commit to the development of system resources.

In emerging technological fields, however, uncertainty is high and system resource creation may be complex, which means that the basis for cost-benefit considerations is rather weak. Furthermore, system resource creation often takes time and involves a range of different actors with different interests. Therefore, it will be unclear at the outset how collective resource(s) will look like and there might even be ample room to shape them strategically. Firms with a wait-and-see strategy run a risk here that 'system builders' will use this leeway in their own interests, thus creating new gravity fields with potential disadvantages for the free-riders. Equally important, organizations that do not take part in resource building may not fully understand the benefits a newly created system resources can provide. System resource creation, in other words, may go hand in hand with the development of specific and complementary organizational resources (competences) in those firms that are actively involved in the creation process.

It has been noted before that system resource creation is often a process, in which different organizations collaborate. In situations of high uncertainty, inter-firm collaboration directed at system formation can be attractive because of the secondary benefits the interaction provides. These may include informational advantages, further contacts, reputational gains and the like. Especially in formal networks dedicated to system entrepreneurship, we expect a strong link between the benefits of system and network resources: commonly developing system resources means getting access to potentially valuable network resources.

Inter-firm networking, however, may also be enhanced through processes of institutionalization. Actors may first collaborate in a way that does not require substantial commitments. The goals of the collaboration may be unambitious or even ill-defined. If initial efforts appear to be successful, however, network members may turn towards more demanding goals. At the same time, interaction becomes more routinized, trust emerges and common governance structures develop. On this basis, firms may then be willing to increase their commitment and the resources they devote (escalating commitment, cf. Wijen and Ansari, 2007). Through this gradual process collaboration becomes more and more institutionalized and the collective action dilemma may be circumvented.

Given the variety of reasons for organizations to commit to the creation of system resources, we conclude that the emergence of technological fields has to be understood as a process of strategic interaction of a broad range of actors.

2.7 Implications of the resource perspective for innovation studies

In this conceptual paper, we have explored how resource-based reasoning can be used to provide new insights for the study of emerging technological fields in general and for the literature on technological innovation systems in particular. Here we summarize our main findings. First, institutional structures (or system resources) in a technological field are of strategic relevance for the innovating actors. Second, we therefore expect innovation systems structures (and system resources) to be strategically shaped by the actors in the field. Third, different actors are likely to play different roles in these processes. Fourth, processes of system (resource) creation are likely to be context-dependent, which has implications for the imitability of successful innovation systems.

A technological field, or innovation system, is more than just a large set of different organizations with sub-sets of organizational resources. The core idea elaborated in this chapter is that assets of strategic relevance (resources) do not just exist at the level of organizations but also at higher levels of aggregation, i.e. in formal networks and at the system level. A technological field is characterized by these system-level resources; they generate and structure the ‘systemness’ that arises over time. Both, system resource structures and field characteristics (e.g. competitive relationships, system boundaries, technology performance) evolve together and change over time.

While system resources may emerge in a rather uncoordinated way, we can also expect that they are often strategically developed by single actors or networks of collaborating actors. Actors that expect high gains and low costs from system resource creation are likely to play a key role here. Furthermore, uncertainty and the risk to be excluded from reaping the benefits of collective resources represent further incentives for ‘system entrepreneurship’. Finally, as the system matures and institutional structures materialize, the strategic commitment of innovators may escalate.

A tenet of resource-based reasoning is that organizational actors are different in terms of the resources they can use. Some of these differences may be persistent because some resources are difficult if not impossible to transfer between organizations. Against this background, it is possible to distinguish organizational actors with regard to the resources they control and we can conclude that different actors play different roles in an emerging innovation system. Some actors may have access to a very specific set of resources (e.g. technological knowledge, firm reputation, customer contacts, IPRs) because of which they can pursue and achieve goals (e.g. create a common vision or shape the reputation of a technology), which other actors cannot. In the innovation studies literature, scholars have referred to prime movers (Jacobsson and Johnson, 2000) or key actors. These concepts exactly reflect the idea that actors may be different and that these differences matter when new technologies emerge.

A crucial consequence is that some actors may be more important than others for an innovation to become realized or, more precisely, for an innovation to develop in a certain way. This argument can even be transferred to the level of resources: some resources may be more important than others for an innovation to develop in a certain way. Where these resources are immobile, rare, difficult to imitate and substitute, the organizations that control them have the potential to play a key role in the field. We may think of ‘critical’ or ‘key resources’ in this regard. A technological standard controlled by a firm and used strategically as in the case of Java technology is an example here (Garud et al., 2002). In many empirical settings, however, it might be difficult to trace the relevance of resources at the organizational level for developments at the level of the technological field.

For network and system resources, similar arguments apply. Some of them may be rare or even unique and of high importance for technology development. Emergent resources at the system level such as collective expectations or a dominant design may potentially play such a role. In the field of innovation studies we find many examples, in which system resources have had a major impact on technology development. A novel environmental technology, for example, may need specific governmental support in the form of financial incentives or emission regulations for established technologies in order to compensate for the positive externalities of its application. Or a new high-tech product may crucially depend on the skills of local service companies for maintenance and trouble-shooting.[23] The crucial issue here is that the formation of such resources may be highly context dependent, i.e. whether supportive structures at the system level emerge at all and how they look like may very much depend on the specific circumstances, the actors involved, their strategies, their interaction etc. This explains for example, why technological innovation systems vary in temporal and spatial terms. Take for example the differences in the development of wind power technology in Denmark, Germany, The Netherlands and the UK (Bergek and Jacobsson, 2003; Garud and Karnoe, 2003).

As a consequence, there might be similar challenges for the imitation of successful technological innovation systems as there are for the imitation of successful firm strategies. Innovation systems that are dependent on complementary, localized resources and competences may be more difficult to expand or to transfer to new contexts than others. These phenomena have for example been highlighted in the literature on industrial clusters (Porter, 1998; Saxenian, 1991) and regional innovation systems (Asheim and Coenen, 2005; Cooke et al., 1997).

The proposed model of resources at different levels of aggregation helps to see the strategic moves of innovation system actors in a new light. However, we are just at the beginning of untangling the relationships between organizational characteristics, firm strategies and innovation system formation in a more systematic way. Further research will be needed to specify the conditions under which firms contribute to system creation and to elaborate on the factors that affect the imitability and transferability of system

[23] This latter example points to the issue of how value chains develop in emerging technological fields.

resources. In addition, the role of key actors or prime movers in innovation systems and the issue of critical resources at the organizational level need to be analyzed in more detail. Similarly, it seems to be promising to study the role of inter-firm collaboration in formal networks and the role of these networks in system formation.

The concept of resources and the underlying ideas of resource-based reasoning are only one way to approach these questions. The resource perspective highlights the benefits of institutionalization processes at the system level but it runs the risk to neglect the constraining effects of system resources, which may occur in the case of common standards, for example (Funk and Methe, 2001).

Additional efforts will therefore be needed to reflect and explicate these and other limitations of our approach (e.g. in terms of the underlying rationality of decision making) and to discuss alternatives. Another inroad to address the relationship between organizations and institutions in innovation systems may be the literature on institutional entrepreneurship (e.g. Beckert, 1999; Di Maggio, 1988; Sine and Lee, 2009). Here, we find comparable accounts of a strategic shaping of emerging technologies and organizational fields.

Interlude chapter 3

The development and diffusion of novel technologies, e.g. for decentralized energy generation, depends crucially on supportive institutional structures such as R&D programs, specific regulations, technical standards and 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 and a positive image of the technology. These elements have been reported to generate positive externalities in the field, 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.

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

3.1 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 and 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), dominant designs Murmann and Frenken, 2006, 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., 2008; 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 sizeable attention in recent years as an analytical framework for the study of emerging technologies (e.g. Carlsson et al., 2002b; Edquist, 2005; Jacobsson and Johnson, 2000; Markard and Truffer, 2008b). In the domain of new energy technologies, numerous cases and 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 co-operations of firms and other actors whose goals are the achievement of common aims (Sydow, 1992). 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., 2008; Hekkert et al., 2007; Jacobsson and Johnson, 2000).

The chapter starts with a theoretical component, in which we elaborate on the conceptual framework our analysis is based upon. This is followed by the methods section. In section 3.4, we introduce our empirical field of study and the networks selected. Sections 3.5 and 3.6 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 3.7 concludes.

3.2 Theoretical background

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

3.2.1 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 processes that are important to the build-up of TIS. The functions are very helpful in tracing the performance of TIS and will be used in the subsequent analysis (cf. section 3.6.2). Table 3 presents an overview and some of the indicators used to track the different functions.

Table 3: Overview of TIS functions

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 related 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 & learning by using in networks	Number of workshops & 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 articles 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.

Source: Adapted from Bergek et al., 2008a; Hekkert et al., 2007

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 the deliberate activities of actors.

In this paper, we argue that actors strategically influence system-level elements (cf. Figure 4). Because they typically cannot achieve this task alone, they join forces in formal alliances, or networks (see below).

3.2.2 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 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 their own resources such as network management, a budget or a webpage to create visibility, etc.

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.

3.2.3 Formal networks: rationale for focus and definition

The analysis in this chapter 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. Figure 4). 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 (Figure 4). 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.

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 co-operations of firms and other organizations with clearly identifiable members and a common aim or strategy.

3.3 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 depicted in Figure 4, 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.

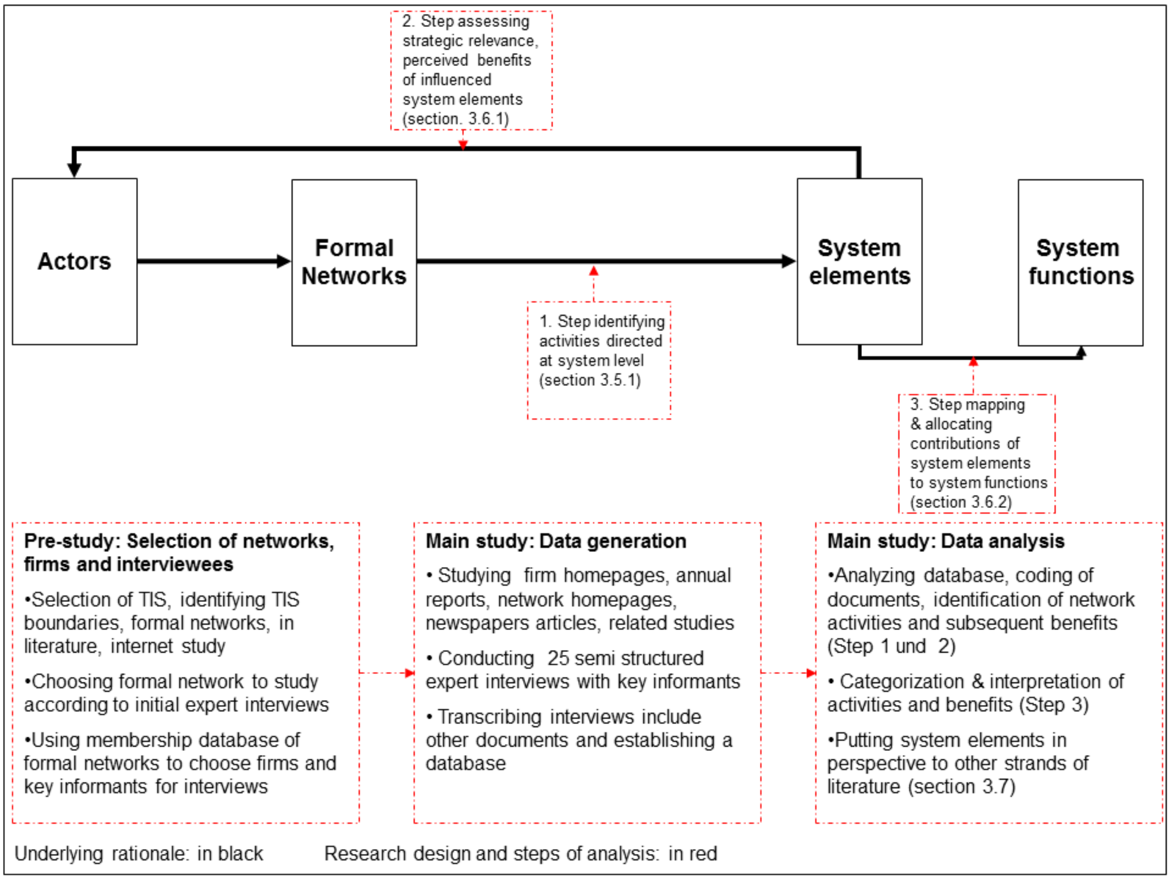

Figure 4: Analytical framework: underlying rationale and steps of analysis

3.3.1 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 very high number of 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 anymore. 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[24] 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 as an important regional network and the VDI[25] committee `fuel cells in the household energy supply` as an example of a technical committee.

3.3.2 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 webpages 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 hours 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). 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 these network activities (steps 1 and 2 in Figure 4). 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 3.5.1).

In the final, more interpretational step (‘data analyses’, Figure 4), the identified activities were used to identify system elements that they created or shaped. This was done in two

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

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

different ways: First, we identified directly created elements of the networks (standards, guidelines are 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 3.2). Finally, we put the identified elements in perspective and related them to concepts in the field of strategic management (cf. section 3.7).

3.4 Fuel cell innovation system and major networks in Germany

The fuel cell is a technology in an early stage 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.

3.4.1 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 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 cogeneration, 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 service providers as well as service providers and intermediary organizations can be differentiated (cf. Figure 5).

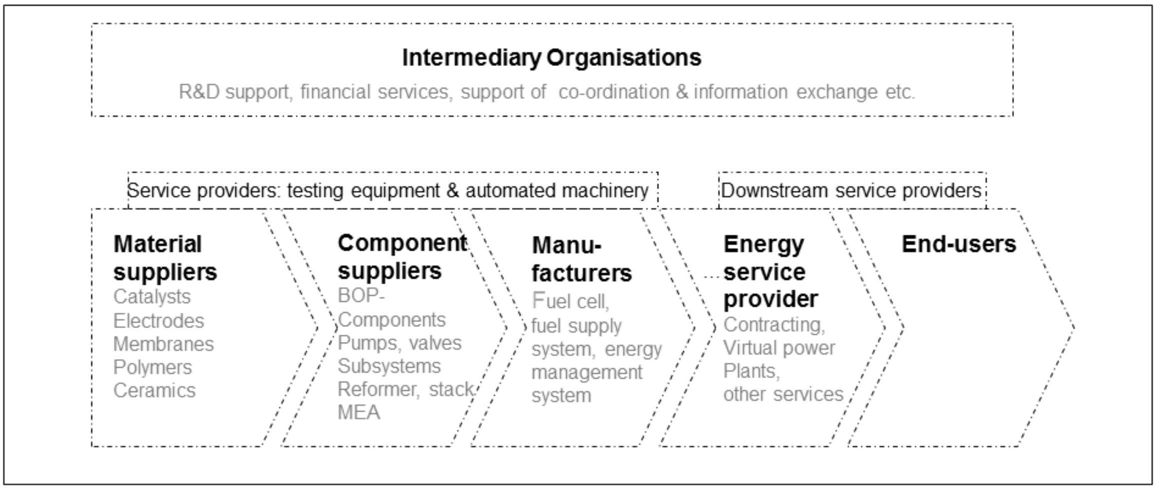

Figure 5: Outline of fuel cell value chain for stationary applications[26]

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 service providers 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. fitters, 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 to the collaborations we observe in the

[26] 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.

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 fitters). 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 service providers 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 fitters) as other decentralized co-generation technologies. Players from the boiler industry as well as energy service providers 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.

3.4.2 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, 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, 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 potential of stationary fuel cells led to their hype in 2000/2001 and subsequent disappointment (Ruef and Markard, 2010). This was accompanied by a cutback 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 million. Euro for three years) went into stationary applications (Ruef and Markard, 2010). Networks were set up, 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 (fuel cell initiative, IBZ) 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 fuel cell initiative (IBZ) 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 programs 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.[27] As a result, 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.

3.4.3 Characteristics and positions of the innovation networks selected

Five networks were selected for an in-depth analysis. Table 4 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 between nine and 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.

[27] 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.

In the VDMA component suppliers, manufacturers and research institutes of all fuel cell innovation systems (stationary, mobile, portable) are organized to conduct lobbying activities and coordinate the value chain. The IBZ fuel cell initiative is a network of major energy service providers 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 service providers 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. Like the VDMA, it is a forum in which upstream actors such as material and component suppliers meet. Here, the network goals are more focused on the organization and support of the regional industry development.

Table 4: Profile of the formal networks in the study

	VDMA fuel cell working group	**IBZ fuel cell initiative**	**Callux**	**VDI fuel cell technical committee**	**Fuel Cell and Hydrogen Network NRW**
Founder /	Association	Industry firms	Industry firms	Association	Regional public authorities
Year of foundation	2003	2001	2008	1997	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, fuel cells
Main actor groups	Materials & component suppliers, manufacturers, research institutes, service providers	Manufacturers, energy service providers, intermediary organizations	Manufacturers, energy service providers	Energy service providers, manufacturers, research institutes	Materials & component suppliers, manufacturers, research institutes, service providers
Network mission	Development of fuel cell industry, industry political interest group, industry network for establishment & optimization of fuel cell value chain and cost reduction of fuel cell systems	Support the introduction of stationary fuel cells based on "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

Source: interviews and homepages of the networks

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.

3.5 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.

3.5.1 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 5). Note that these types were derived solely from our empirical material, although some notions are similar to the system functions (cf. section 3.2).[28]

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. Also, 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 service providers, 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

[28] 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.

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 fitters and architects through the publication of guidelines, for example, 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 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 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 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 has successfully established an advocacy coalition (Sabatier and Jenkins-Smith, 1993; 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 the NIP and has influenced the decision that one third of 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.

Table 5: Activities of the networks with expected system-level effects

Main activities	VDMA fuel cell working group	IBZ fuel cell initiative	Callux project network	VDI fuel cell technical committee	NRW fuel cell network
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 & 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 & execute joint lighthouse project • Use of experiences of field tests to improve prototypes • Develop interface for data transfer (Callux box) • Develop technical solutions for desulphurization of natural gas (associated NIP project) • Specify content for vocational training	• Integrate knowledge and experiences for drafting service contracts • Specify, produce and use reference load profiles of German households • Specify, produce and use simulation software for testing & 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 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 test modules	• Produce and publish technological guidelines about drafting service contracts & use of reference load profiles • Produce guidelines with attached planning tool for service providers (simulation software for dimensioning of micro-CHP)	• Conduct seminars & conventions and other services • Provide database with members and fuel cell products • Offer advice for new entrepreneurs in the field
Marketing & 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 & produce content for joint press releases	• Employ a PR agency • Run Callux webpage and info-hotline • Produce Callux fuel cell field test movie • Coordinate & 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 & 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 • 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 & integrate newcomers • Initiate exchange and facilitate pre-selection of partner • Initiate harmonizing of specifications, facilitate introduction of common standards • Organize and supervise small-scale device program (KGP)	• Develop technological norms and standards • Evaluate project proposals in small-scale device program (KGP)			• Motivate, integrate and support entry of newcomers • Bring interested parties together (brokerage of partners) • Coordinate regional projects

Source: interviews

Subsequently, members have been engaged in the definition of joint problems in specific working groups. 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 then 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 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.

3.5.2 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. Figure 6 depicts these new system elements. Those that were under the rather direct control (black solid arrows) of our networks are colored in green, whereas those that were influenced to a finite extent (grey 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.

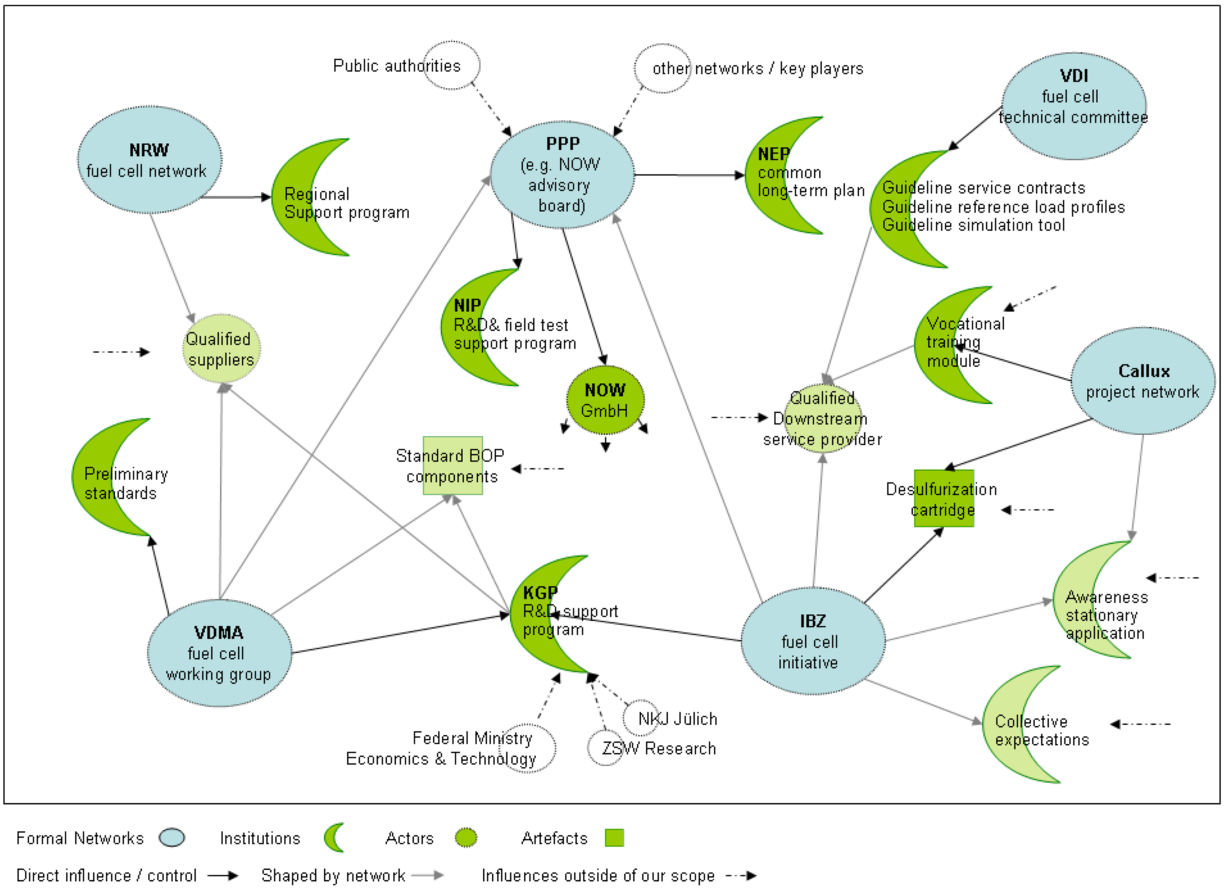

Figure 6: Selected formal networks of the stationary fuel cell TIS in Germany and their role in creating new system-level elements

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 officials and representatives of the German fuel cell industry meet regularly to decide on the strategic orientation of the NIP, among other topics. 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, 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.

3.6 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.

3.6.1 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 cooperated in formal networks to create them, we use statements from the interviews.

Different firms support the TIS build-up process through networks. Energy service providers conduct activities in networks to stabilize and support the manufacturers; to influence collective expectations; and finally to assign roles to fitters and architects. Fuel cells, virtual power plants and contracting models are central elements of the business strategy of an important energy service provider 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 service provider: During that time [after the hype], we tried to stabilize the manufacturers as well as the energy service providers through the IBZ. During that time, we founded the regional initiative, then the Fuel Cell Alliance Germany, from which

> the NOW was eventually also 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 to the manufacturer: Attention, here is a market waiting - you just have to get the technology finished."

Critical for the realization of the business strategies of committed energy service providers 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 service provider had to intervene within the IBZ fuel cell initiative:

> Project manager of an energy service provider: "Without the IBZ, all larger developers had ceased their work after [the breakdown of] the hype in 2002 ... The IBZ signaled that energy services provider 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 technology."

The last quotation indicates that expectations are important system elements. 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 service providers and manufacturers also became active here:

> Product manager of a manufacturer: "We have integrated corporate communication and IBZ communication. This was absolutely necessary: we could not continue trying to outdo each other with hyped statements, like competing market stallholders. We had to establish the platform [to coordinate communication] and tune expectations down. ... [However,] remaining silent was not an option either. Then, we would have fallen even deeper. Now, we are avoiding passing the valley at its deepest point, because we have a common communication strategy."

For the business strategies of energy service providers and manufacturers, the integration and qualification of service providers is also a strategic issue. It is expected that energy service providers that co-operate at an early stage with fitters and architects obtain an advantage due to the developed routines and reputation. 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 service provider: "For fitters and market partners, we have educational programs. ... Fitters need to be competent in order to install/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 fitters 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 fitters so that they [fitters] know what they are doing, and also so the developer knows what the craftsman is doing - to have it under control."

The commitment and support of major component suppliers was also important to set up the TIS of stationary fuel cells. Some suppliers already provide marketable components for stationary fuel cells. A central bottleneck for these firms is, however, the demand for stationary fuel cell systems. 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 KGP R&D support program (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 [work together] 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 a national level."

Programs like the KGP can build bridges, as they provide financial support and stimulate co-operation 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 components is supervised by IBZ and VDMA. A larger picture behind this is that 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 being [deliberately] pushed; there is a broader interest behind it. - This is what you build a management decision on."

Above all, the quotations exemplify that formal networks have been used to create system elements for strategic reasons. However, most strategic decisions have been driven by the goal of establishing the technology field and not primarily of serving particular firm interests. 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 fitters (cf. Figure 6). Furthermore, it was reported that the system elements provide benefits 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.

3.6.2 System-level contributions of the identified elements

In section 3.6.1, we have illustrated some of the effects the networks generated as they started to actively shape the innovation system on stationary fuel cells. In Figure 6, 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, guidelines), but also informal, cognitive structures (collective expectations, awareness and image of technology). Furthermore, specific artifacts were developed and new organizations and even new networks were created. For each element, we also listed which system functions were affected (cf. Table 6). 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 3).

The general pattern that emerges from the analysis above is that most of the system elements contributing to the system functions are 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. Produced and shaped elements such as the KGP support program, the Callux vocational training module, in addition to the activities of the VDMA in integrating newcomers and introducing common technological standards reveal that the integration of suppliers, the modification of existing standard components, as well as the assignment of specific tasks in the value chain are processes that are actively coordinated and pushed by formal networks at the system level. 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.

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 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.

Table 6: Different types of system elements created and shaped by innovation networks

General type	Description	Examples	TIS function positively affected
R&D & field-test support program	Formal institutional structure that provides financial R&D & 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]

Source: interviews

3.7 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 service providers 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.

3.7.1 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 3.2). 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 adequately investigated 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 sizeable task sharing among the networks (cf. section 3.5.2), 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. So, 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., 2012).

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 3.2.1). 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; Markard and Truffer, 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, standardized products, reputation in the high-tech field, as well as support programs is a valuable resource 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 and Eriksen, 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.

3.7.2 Implications for further research and policy making

In the 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 that 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.

Interlude chapter 4

Previous research has shown that formal networks can play a crucial role in the formation of technological innovation systems (TIS). Firms and other actors collaborate in formal networks not only to generate new knowledge but also to strategically create and shape supportive system resources such as technology specific R&D programs. This chapter takes a closer look at the resources, which are developed and deployed by networks to facilitate the building up of a TIS. Networks rely not only on the organizational resources of their members but also on new resources developed at the network level including network governance structures, trust among network members, a common understanding of the strategic goals or a good reputation of the network. Our analysis shows that the capacity of networks to fulfill different tasks of system-building especially depends on the network resources they are able to establish. With the differentiation of organizational, network and system resources we introduce a conceptual framework, which makes three important contributions. It highlights the strategic nature of (innovation) system-building; it allows us comparing the contribution of different actors and formal networks in this regard; and it improves our understanding of how firm and system level processes are intertwined.

4 Networks and network resources in technological innovation systems: towards a conceptual framework for system-building

4.1 Introduction

New technologies often have a hard time to develop and diffuse, especially if they are fundamentally different from established technological structures in a field. In early stages of development, performance of a new technology might be low, market prospects unclear and contexts of use still ill-defined. At the same time, competing established technologies are well supported and stabilized by the wider socio-technical regimes with which they have evolved (Rip and Kemp, 1998). In the case of environmental innovations that generate positive externalities, e.g. as they generate less emissions than established technologies, the challenges are even more pronounced (Kemp et al., 1998). For the development and diffusion of such ‘clean’ technologies and a potential transition towards more sustainable modes of production and consumption, supportive structures which legitimize and stabilize the emerging technology have to be developed – be it in regulatory terms cf. (Nill and Kemp, 2009; Walz, 2007) or in the broader sense of an infrastructure for innovation (Van de Ven et al., 1999).

A crucial point is that technology-specific support structures can neither be taken for granted nor treated as being external to the process of technology development (Van de Ven, 1993). Instead, they are created and shaped by firms and other actors with a stake in the novel technology (e.g. Garud et al., 2002; Rao, 1994). Innovating actors, in other words, often commit themselves to system-building as they set up or adapt broader institutional structures that support the emerging business field (Hellsmark and Jacobsson, 2009; Hughes, 1979; Musiolik, 2011; Musiolik and Markard, 2011).

The process of system-building and the development of new technological fields can be studied with the help of the literature on technological innovation systems (Carlsson et al., 2002a; Markard and Truffer, 2008b). The innovation systems approach highlights the role of institutional structures and the importance of actors for the emergence of technological innovations. A key interest is to identify system failures in the emergence of new technologies and to derive recommendations for technology-specific policies (Bergek et al., 2008a; Jacobsson and Bergek, 2011).

For single actors, system-building is often very difficult to achieve, which is why they cooperate with others in this respect (Van de Ven, 2005). Informal networks or personal linkages (Granovet.Ms, 1973) are as important here as formal networks of innovating firms. While in the innovation literature, inter-organizational networks have received quite some attention as they facilitate interactive learning and knowledge generation (Lundvall, 1992) the role of networks in supporting collective action and system-building has been less in focus (Ozman, 2009). We believe that a systematic analysis of formal networks, i.e. visible organizational structures where firms and other actors come together to achieve common aims, is important to better understand processes of innovation system-building.

In Musiolik and Markard (Musiolik and Markard, 2011) it was shown that formal networks played a crucial role in the emerging technological field of stationary fuel cells as they developed technical standards, specific R&D programs or educational programs, for example. These structures, which were set up as a result of a broad range of activities at the level of different networks, were conceptualized as system resources, which positively contributed to some key innovation system functions (ibid). Some of these networks have been able to exert influence widely, whereas others have only had an effect on one or two system resources. In this chapter we follow up on the latter by asking *why networks differ in their abilities to influence system resources and which kinds of formal networks might be important for the build-up process of an emerging TIS*. In particular, we want to look into processes at the network level to understand how they develop and combine different kinds of resources, which are key for the emerging competences of networks and their ability to create and shape supportive structures at the innovation system level.

To this end we combine concepts from the literature on strategic management (Barney, 1991; Dyer and Singh, 1998; Wiltbank et al., 2006) with the innovation systems literature. The literature on the resource based view (RBV) offers valuable insights into a resource-oriented perspective on innovation system-building (Markard et al., 2011; Musiolik and Markard, 2012). Following the ideas of the RBV, resources at the organizational level are developed and deployed for strategy making, and set limits to what a firm can do (Dierickx and Cool, 1989; Peteraf and Barney, 2003; Rumelt, 1984a). Strategically relevant resources, however, may not just be located at the firm level but also beyond, i.e., in inter-firm networks (Dyer and Singh, 1998; Gulati, 1998, 1999) or even at the level of innovation systems or industries (Foss and Eriksen, 1995; Musiolik and Markard, 2011). For emerging technologies this broader resource space Foss and Eriksen, 1995 is important as system-building can be regarded as a resource driven process. In an environment characterized by a high level of uncertainty and ambiguity (Meijer et al., 2007a, b; Santos and Eisenhardt, 2009), key actors may start from the resources they have available and continuously extend these resources while interacting with other organizations (Sarasvathy and Dew, 2005). This strategy -- forging networks of actors and setting up a cycle that increases the resources available -- reduces ambiguity, uncertainty as the technological field is co-created (Wiltbank et al., 2006).

In our empirical study we focus on a selection of five major formal in the emergent field of stationary fuel cells in Germany. Prior analyses have identified this field as highly dynamic (Brown et al., 2007; Markard and Truffer, 2008a; Nygaard, 2008) and demonstrated the importance of system-building in this case (Musiolik and Markard, 2011). In addition to that, agents of different technological applications (portable, stationary and mobile fuel cells) are currently competing for public support (Garche et al., 2009; Musiolik and Markard, 2011). Trust, joint knowledge, power and reputation might be resources drawn on at the network level to develop the field. In the study interviews have been carried out to capture in detail the resource endowment of members, the establishment of resources at the network level and finally their deployment towards system build-up.

The remainder of the chapter is structured as follows. Section 4.2 starts with a brief review of the TIS- and the RBV literature and also specifies our analytical framework. In section 4.3, we describe some features of the networks selected and the context they are operating in. Sections 4.4 and 4.5 present the results of the empirical analysis: here we report on the different resources used in the selected innovation networks, using two examples to show how these resources have been deployed to influence system resources. We also take initial steps towards generalizing our results, and delineate different types of resources and the role that the different networks play in TIS development. Section 4.6 concludes.

4.2 Theoretical background

In the following section, we briefly introduce the technological innovation system concept and the resource concept in the RBV literature, and also specify our analytical framework that links resources at different levels in TIS in our quest to analyze the processes of system-building.

4.2.1 Technological innovation systems and the role of formal networks for system-building

The technological innovation system (TIS) perspective highlights the dynamic interplay of actors and broader institutional structures in technological fields (cf. Carlsson and Stankiewicz, 1991; Edquist, 2005). A TIS can be defined as 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” (Markard and Truffer, 2008a). Key structural elements of technological innovation systems are actors and institutions. Actors include different kinds of firms, universities and research institutes, financiers, consultants, associations, private consumers and public facilities with different competencies, resources and strategies. Institutions facilitate but also constrain the decisions and activities of actors and include technical norms, standards, regulations, values, collective expectations, cognitive frames, culture etc.

The innovation systems approach was developed to highlight the institutional and collective aspects of innovation. In their quest to explain a certain course of technology development, most TIS studies concentrate on the system level as the core unit of analysis. A key interest is to identify system failures in the emergence of new technologies and to derive recommendations for technology-specific policies (Bergek et al., 2008a;

Hekkert et al., 2007; Jacobsson et al., 2001). System failures, for example, originate from the role of networks. Weak networks can lead to an insufficient use of complementary resources among actors and thus hamper innovation, while over-strong networks may result in a blindness towards external developments, which also affects innovation system performance negatively (Carlsson and Jacobsson, 1997).

In the following we will argue that, in order to better understand and improve system performance, we have to look into the processes through which technological innovation systems are intentionally created. Actor strategies directed at system-building have attracted the attention of TIS scholars just recently (Markard and Truffer, 2008a; Musiolik and Markard, 2011; Hellsmark and Jacobsson, 2009). From inquiries in management studies and other disciplines we know that organizations strategically shape the technological field they are operating in: they control the emergence of new technical standards (Garud et al., 2002), introduce and legitimate new practices (Maguire et al., 2004), establish new values and business models (Kaplan and Murray, 2010) or influence collective expectations (van Lente and Rip, 1998b; Borup et al., 2006). Again these supportive structures provide positive externalities for a collective and can be framed as system resources (Musiolik and Markard, 2011). However, if we know why and how specific system resources came about, we will better be able to inform strategies to increase system performance.

A second point we make is that formal networks are likely to play a key role in such processes of system-building because they enable actors to coordinate their strategies and organize collective action (Musiolik and Markard, 2011; van der Valk et al., 2010; Weber, 2002). Traditionally, the TIS literature has conceptualized networks as informal structures, which facilitate the exchange of information, knowledge and other resources between innovating actors (Carlsson and Stankiewicz, 1991). In contrast to that approach, we use the notion of *formal networks* to highlight that networks can also represent a source of agency in TIS, especially when these networks have the goal to change TIS structures. We define a formal network as an organizational structure with clearly identifiable members where firms and other organizations come together to achieve common aims or to solve specific tasks. From a RBV perspective formal networks can also be conceptualized as bundles of resources which are made available by the network members or which emerge in the network. These resources depend, among other things, on the composition of organizations that form the network (van der Valk et al., 2010). On the basis of this concept we can assume that the system-building capacity of a (formal) network is determined by the resources that are available for such kinds of tasks.

The notion of resources already plays a role in the TIS literature. Resources are typically referred to as inputs such as financial or human capital which are needed for the development of a particular technology (Bergek et al., 2008a,Hekkert et al., 2007). How resources are developed or strategically deployed has not received much attention. Instead, it is implicitly assumed that the necessary resources exist ‘somewhere out there’ with the major challenge being that they must be made available for the new technology, e.g. through public R&D support or educational programs (Hekkert et al., 2007).[29] In the following, we add a new, more dynamic perspective on resources as assets which are strategically developed, used and transformed by actors in the innovation system. They facilitate technology development but also determine the range of strategic activities that innovating actors and formal networks can pursue in a given situation. In this new perspective, resources such as common culture, trust, shared goals or reputation also appear as important factors for the successful development of a new technology, next to financial and human resources.

4.2.2 Resource based reasoning: basic concepts

The resource based view (RBV) is a key approach in the management literature to explain the competitive advantage of firms (Barney, 1991; Barney, 1986b; Kraaijenbrink et al., 2010; Newbert, 2007; Peteraf, 1993; Wernerfelt, 1984). Its two major underlying assumptions are that firms control different resources and that these differences may persist over time because some resources are difficult to transfer or even immobile (e.g. Barney, 1991; Dierickx and Cool, 1989, Peteraf, 1993). Resources are strategically developed and accumulated within the boundaries of firms. They enable a firm to develop a strategy and to accomplish its aims (Dierickx and Cool, 1989; Rumelt, 1984a). Below we use resource based reasoning, although our primary interest is in resource development and re-configuration processes in innovation systems, not in the competitive advantage of firms.

The concept of resources has been defined in different ways and the RBV has faced quite some criticism for its all-encompassing resource definition (Barney, 2001a; Kraaijenbrink et al., 2010; Priem and Butler, 2001b). For the following we use the definition below:

> Organizational resources are tangible and intangible assets that are owned or controlled by an organization. They are of strategic value and enable an organization to conceive of and implement strategies that improve its efficiency and effectiveness.

Tangible resources are often visible and can be quantified (Barney, 1991,Grant, 1991). They include financial assets and all kinds of equipment such as plants, machines etc. Intangible resources are deeply rooted in a firm’s history and encompass (accumulated) immaterial assets such as patents, know-how, firm culture or the reputation of a firm. Intangible resources can be distinguished further (Hall, 1992, 1993): human resources subsume all the skills, knowledge and the motivation of a firm’s employees; they are inseparable from its bearer. Structural resources (e.g. firm culture, routines or norms and guidelines) characterize the intra-firm context the employees work in. Relational resources, finally, refer to the extra-firm context and include the potentials derived from

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[29] Resource mobilization is referred to as one of the key functions that determine the performance of a TIS (e.g. Bergek et al., 2008a).

the relationship to customers, suppliers and other organizations. They include customer or supplier loyalty as well as the reputation of a firm or brand (Fernandez et al., 2000).[30]

While resources at the firm level are central in the RBV literature, the resource concept has also been applied to higher levels of aggregation including inter-firm networks (Dyer and Singh, 1998; Lavie, 2006; Lavie, 2008) and industries (Foss and Eriksen, 1995). The underlying idea is that strategically relevant assets can also be produced beyond firm boundaries. In alliances or networks, firms not only get access to resources of their partners (Lavie, 2006) but also to resources that emerge through the interplay of cooperating actors (Dyer and Singh, 1998).[31] At the industry level, collective resources emerge additionally through the interaction of multiple actors and their effects become apparent in industrial districts and clusters (Asheim and Coenen, 2005; Porter, 1998). The concept of industry resources is comparable with the idea of system resources in technological innovation systems (Musiolik and Markard, 2011).[32] Both provide benefits and can be used by a broad range of actors in a field, typically without any restriction of access.

To conclude, resources at different levels have been conceptualized in the literature. Organizational resources are strategically accumulated or produced within firms. Network resources, such as trust among network members or a common vision, are developed within formal networks. Industry or system resources, finally, are collective assets which are often deliberately created to support industry or technology development.

4.2.3 System-building and the role of resources

System-building is the deliberate creation or modification of broader institutional or organizational structures (system resources) in a technological innovation system carried out by innovating actors. It includes the creation or re-configuration of value chains (Hajek et al., 2011,Musiolik and Markard, 2011) as well as the creation of a supportive environment for an emerging technology in a more general way (Hughes, 1979,Van de

[30] Recently also the importance of power as a relational resource was pronounced (Bathelt and Glückler, 2005). Power was here defined as social practice of building networks and enrolling other actors in joint projects.

[31] In the literature networks are conceived as both: formal alliances and also as informal networks, the social context a firm is embedded in. As a result resources at the network level are delineated in the form of inter-firm complementarities (Dyer and Singh, 1998) but also as 'network resources' (Gulati, 1999a) type of a resource which results from the informal advantages firms obtain from their (informal) social ties (cf. Borgatti and Foster, 2003 and the literature on social network analysis)

[32] Note in the case of new technologies or industries collective resources might not emerge due to local linkages at a regional level. Instead in high technology small and medium sized enterprises (SMEs) have often nationwide linkages (cf. Wever and Stam, 1999).

Ven, 1993). System-building may be the result of largely autonomous key actors (Hughes, 1979,Hellsmark and Jacobsson, 2009), but more often it is a collective approach, in which organizations coordinate themselves in bilateral or multilateral interaction (Hajek et al., 2011,Musiolik and Markard, 2011,Weber, 2002,Van de Ven, 1993).

For system-building activities the deployment of resources is crucial. Following the ideas of Sarasvathy and colleagues (Sarasvathy, 2001, 2008; Sarasvathy and Dew, 2005; Wiltbank et al., 2006) market creation (system-building) is a means driven process: in the case of radical innovations, innovating actors start from the means (resources) they control and continuously extend these means while engaging with other stakeholders in networks (Sarasvathy and Dew, 2005). Innovating actors, therefore identify, develop and use resources at the organizational, network and system level to steer and control the development of a new TIS. Again, crucial are the available resources (at these different levels) which determine the system-building activities of innovating actors. By analyzing the engagement of innovating actors in formal networks, we can focus on the interplay of resources at different levels (organization, network and innovation system), which in turn provide a better understanding of the system-building process and the different roles of networks and actors.

4.2.4 Analytical framework and method

In the following empirical analysis we focus on formal networks, although we acknowledge that autonomous activities of single actors might also contribute to system-building. Figure 7 presents the analytical framework in which resources at the organizational (in red), network (in blue) and system level (in green) are distinguished. Innovating actors make some of their organizational resources (e.g. knowledge) available to others as they cooperate in formal networks. These networks are used, among other things, to create and shape system resources (e.g. a specific support program for fuel cells). As the actors collaborate in networks, they also establish network resources (e.g. mutual trust, reputation), which may be crucial for the effectiveness of the network in terms of system-building. A network can use its reputation, for example to make policy makers adapt regulations so that they support the diffusion of the new technology.

To apply the analytical framework and to study the different roles of formal networks in system-building we selected the TIS of stationary fuel cells in Germany for a multiple case study (Eisenhardt, 1989; Yin, 2009). In the broader field of stationary fuel cells, around 50 formal networks could be identified (Musiolik and Markard, 2011). Each of these networks has a clearly identifiable set of members (typically firms) and some kind of common goal or mission. Many networks also have a formal network management and structures that regulate ‘network functioning’, e.g. how members interact. A pre-study was conducted to identify key networks with a clearly traceable role in innovation system-building. On this basis, five networks were selected for an in-depth study.

Our main data source is 30 interviews with key informants (e.g. active network members and professionals in intermediary organizations or associations). Interviewees were asked what the networks had achieved in the field, with a particular focus on how networks were able to accomplish the various tasks at the system level. We also traced which network members contributed to the networks, and whether specific structures and competences developed over time at the network level. All interviews were fully transcribed and compiled in a database together with other documents (e.g. newsletters, information from websites, newspaper articles).

In the subsequent analysis the analytical framework was used to identify resources which were instrumental for system-building activities. Resources that remained under the control of an organization (e.g. firm reputation, firm experts), but which were important to fulfill the identified system-building tasks (Musiolik and Markard, 2011), were classified as organizational resources. Resources that emerged at the network level and became inseparable from the network (e.g. reputation of the network, network mission, trust among network members) were classified as network resources. As we asked various members of the networks and incorporated their different perspectives we were able to triangulate our data and to assign common labels to text units that referred to similar resources (Miles and Huberman, 1994; Strauss and Corbin, 1996). After we identified the resource portfolios of the networks, we compared the networks according to their system-building capacities, and delineated different types of networks.

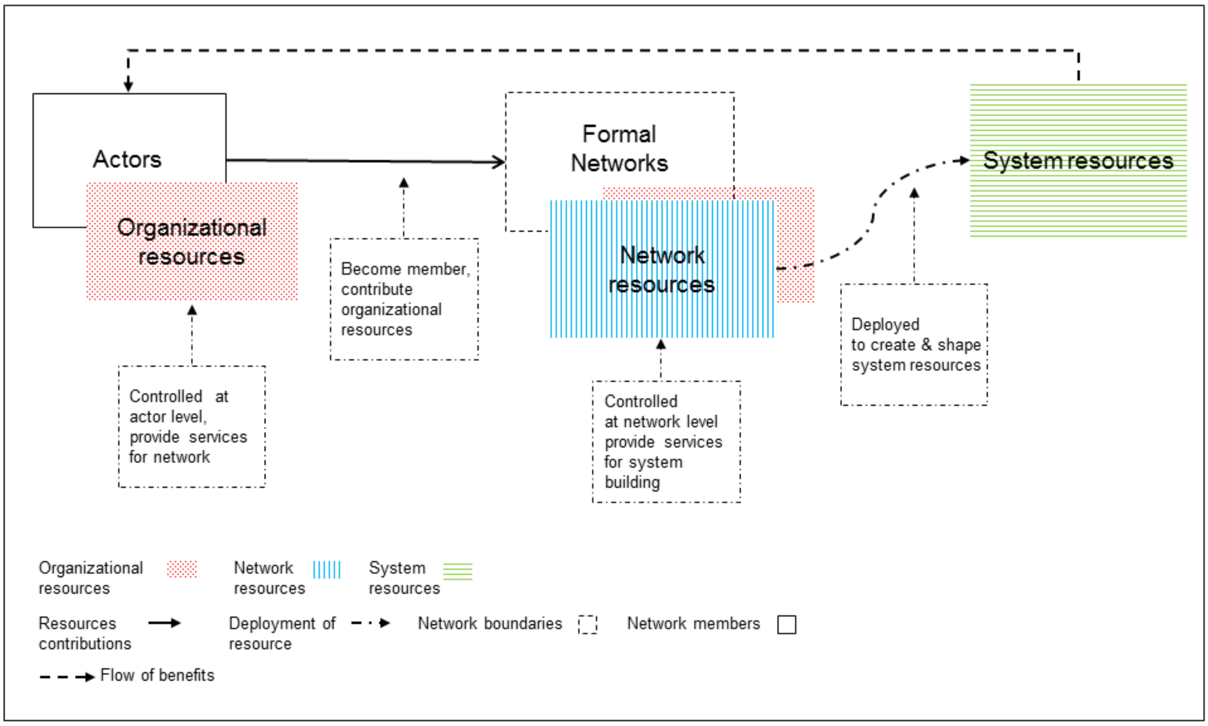

Figure 7: Analytical framework

4.3 Key networks and created and shaped system resources

Stationary fuel cells are small-scale devices for single or two-family homes which generate heat and electricity from natural gas and are based on cogeneration, i.e. the combined generation of heat and power (CHP). In Germany several hundred of stationary fuel cells are currently installed in field tests, while the technology still faces many technological and organizational challenges. Fuel cell manufacturers, for example, are currently struggling to meet the performance standards of conventional boiler heaters in addition to reaching an acceptable price of stationary fuel cells. Despite these obstacles a supportive technological innovation system has been established with many different actors, networks and specific institutions (Brown et al., 2007,Hendry et al., 2008,Nygaard, 2008,Markard and Truffer, 2008a). Formal networks played a key role in system-building and the creation of system resources (Musiolik and Markard, 2011).

4.3.1 Key networks in the TIS on stationary fuel cells

Major TIS build-up activities were triggered through a fuel cell hype in 2001 (Ruef and Markard, 2010). Both politicians and firms became confused during the hype and subsequent disappointment cycle. The ambiguity of this situation was accompanied by the uncoordinated emergence of networks, and a diffuse articulation of different needs and expectations. Coordination and structuring of the field, as well as the institutionalization of key networks, became an important step: networks were consolidated and the VDMA fuel cell working group became the leading network of technology developers (suppliers and manufacturers), while key actors of the stationary and mobile application were already organized in their pursuit of public support and attention (e.g. IBZ fuel cell initiative, networks of the automotive industry). The Fuel cell and Hydrogen network NRW, in addition to the VDI technical committee and Callux, were less important here, except for complementary system-building tasks. Table 7 briefly introduces the networks that were part of our study, all of which play a key role in the innovation system.

Table 7: Features of the formal networks selected

VDMA fuel cell working group	**Key industry network** of technology developers (stationary/portable application), emerged in an ongoing institutionalization process, driven and supported by the VDMA association. Long-term orientation: supporting the creation of fuel cell industry in Germany.
IBZ fuel cell initiative	**Strategic alliance** of key energy service providers, manufacturer (stationary application), established on the initiative of energy service providers, driven by joint interests of members. Long-term orientation: supporting the introduction of stationary fuel cells onto the market.
Fuel cell and Hydrogen network NRW	**Regional network** of technology developers, energy service providers (all applications), founded and driven by public authorities in North Rhine Westphalia (NRW). Long-term orientation: positioning NRW as a hub for fuel cell technology.
Callux	**Project network** and joint field test of some IBZ members (stationary application), established on the initiative of a leading energy service provider. Short-term to mid-term orientation: providing an initial market, preparing fuel cell market and improve end product.
VDI fuel cell technical committee	**Technical committee** under the roof of the VDI association, driven by energy service providers, manufacturer with interests in market preparation for micro CHP technologies (stationary application). Short-term to mid-term orientation: establishing certain guidelines for market preparation.

Source: interviews and network homepages

The networks selected played different roles in system-building, accomplishing tasks in varying degrees of cooperation with each other. Two of the networks not only shaped and created different system resources, but also became embedded in a new governance structure of a national support program. That is why we briefly report on how networks worked together building up a National Innovation Program (NIP) Hydrogen and Fuel Cell Technology. We then go on to introduce other system resources which they had created and shaped in a less cooperative way.

4.3.2 Created and shaped system resources

Networks in the field of fuel cells usually compete for public awareness and support. In the Fuel Cell Alliance Germany, however, they cooperated to set-up a National Innovation Program (NIP) Hydrogen and Fuel Cell Technology and a roadmap, the National Development Plan (NEP) as important system resources (Garche et al., 2009; Musiolik and Markard, 2011).[33] In order to implement the NIP, and to prevent inefficiencies due to the competition between different applications and networks, an intermediary organization, the National Organization for Hydrogen and Fuel cells (NOW GmbH), as well as the NOW advisory board were additionally created as elements of a new (field wide) governance structure (system resource).

In the NIP research, development and demonstration of fuel cells are closely interlinked and supported by public authorities. The aims and activities of the program are structured in the NEP, which also represents the basis for the Federal Government's allocation of funding. A further system resource, the NOW intermediary organization, was created for the implementation of the NIP and the selection of the founded R&D- and demonstration projects. Callux, finally, a joint field test of IBZ members, is the key stationary fuel cells demonstration project supported by the NIP program.

Elements of the NIP and the formal networks are interlinked and work jointly together to develop the field of fuel cells. While the NOW intermediary organization implements the NIP support program, it is controlled by the Federal Government, and steered by the NOW advisory board. Here main representatives of the networks (e.g. IBZ and VDMA), and also of the regional networks and the automotive industry (mobile application of fuel cells), discuss how the NEP common long-term plan is optimized, and solve conflicts in the management of the NIP etc. The NOW advisory board is, therefore, an important communication and coordination channel in the field. Information and requests are channeled between the network members, the NOW GmbH and the Federal Government, while the key networks exert agency and influence the direction of NIP implementation.

In addition to the NIP activities the selected networks also performed system-building tasks alone. As the VDMA organizes the fuel cell technology developers, system-building

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[33] The lobbying activities of this advocacy coalition (Sabatier and Jenkins-Smith, 1993; Jacobsson and Lauber, 2006) were useful to bundle lobbying activities and to speak with one voice to politicians.

was also realized in the field of value chain coordination, i.e. standards and component adaptation (e.g. valves and pumps), and supplier qualification. The IBZ has influenced system resources in co-operation with the VDMA fuel cell working group (e.g. NIP, NEP and NOW GmbH). However, important specific system resources, such as (positive) collective expectations and the awareness of stationary fuel cells, have been additionally shaped. While the IBZ network was very successful in lobbying for support within the NIP program (Musiolik and Markard, 2011) a joint field test project (Callux) was additionally implemented. The Fuel Cell and Hydrogen Network NRW, as the biggest regional network, is steering an influential regional support program and is also contributing to the qualification of suppliers. Finally, guidelines have been established through the VDI technical committee. They make the achieved state of knowledge in a new field explicit, and are often supplemented with artifacts (e.g. tools such as simulation software). Artifacts and the combined knowledge contribute to the assignment of roles for the downstream service providers.

4.4 Resource portfolios and their deployment

In the following we take a closer look at how the networks were able to create and shape the aforementioned system resources. What were the supportive structures and the resources they drew upon to achieve their goals?

4.4.1 Resource portfolios of the networks selected

For each network, Table 8 lists those resources that were used for system-building, according to what was reported in the interviews. The analysis shows that in each case a broad range of different resources was used. In the table we differentiate between organizational and network resources and assign the various resources to some overarching categories from the literature (i.e. tangible, human, structural and relational resources, cf. chapter 4.2.2).

Tangible resources such as financial capital included fees paid by the firms that are members of the network, as well as finances from public authorities or support programs. These organizational resources were used to employ a service provider for the production of a joint software tool in the case of the VDI technical committee, or to employ a network manager in the VDMA example. In addition to that, other tangible resources such as standard components were provided by members but also jointly created at the network level in the case of the IBZ Info-CDs for communication purposes.

Human resources included all the individuals, representatives of the different member firms, and experts with partly different skills, competences and knowledge in each of the networks. In addition to that joint knowledge was also established thought the collaboration of theses heterogeneous experts within the networks: the interaction of suppliers and manufacturers in the VDMA working group had uncovered a joint understanding of cost drivers and the need of standardization of fuel cells, while in the IBZ case, knowledge in joint product development (e.g. fuel cell systems in virtual power plants) was revealed (Musiolik, 2011).

Table 8 : Resource portfolios of the networks selected

	VDMA fuel cell working group	IBZ fuel cell initiative	Fuel Cell and Hydrogen Network NRW	Callux	VDI fuel cell technical committee
Tangible resources	• Fees of members • Specifications, data of systems & components • Artifacts e.g. joint connector technique (Preliminary standards)	• Fees of members • *Joint artifacts PR & communication e.g. homepage, hotline, Info-CD, joint booths at trade fairs*	• Financial support of local authorities • *Joint artifacts e.g. homepage & data base of competence & products of fuel cell firms*	• Financial support of members & subsidies NIP • Artifacts e.g. Callux box (Preliminary standards) • Field test pilot plans and pilot costumers	• Financial support members • Data for reference load profiles • *Joint artifacts e.g. simulation software*
Human resources	• Skilled experts working groups & their knowledge, information • *Joint knowledge: requirements & cost drivers of fuel cell systems*	• *Skilled experts PR & technique & their knowledge, information* • *Joint knowledge: product development & application*	• Skilled experts working groups & their knowledge, information	• Skilled PR & technology experts & their knowledge, information • *Joint applied knowledge from field tests*	• Skilled experts standardization & guidelines • *Joint knowledge e.g. reference load profiles*
Structural resources	• Governance structure: steering committee & emerging working groups • *Network culture & procedure to exchange specifications* • Common understanding of goals at system level • Support of VDMA network manager	• *Governance structure: Steering committee & working groups, network culture to divide tasks, common understanding of goals at system level* • *Trust & stabilization of members*	• Governance structure: yearly meeting of members, working groups • Support of NRW network management	• Callux governance structure to conduct field tests & to realize joint support measures • Coordination & support ZSW institute	• VDI governance structure: procedure to establish & publish guidelines • VDI network management support • *Common understanding of goals market preparation*
Relational resources	• Reputation of VDMA association • *Reputation of VDMA fuel cell working group as professional organized interest group* • Relationships of VDMA network manager to politicians • *Power as accepted & legitimized network of suppliers (critical mass of industry firms)* • *Fuel Cell Alliance Germany (advocacy coalition)* • *3 seats in NOW advisory board*	• *Reputation as competence center for stationary fuel cells* • *Power as key network in stationary field (alliance of key actors)* • Power and influence of members • German Energy Agency (DENA) relationships to politicians • *Fuel Cell Alliance Germany (advocacy coalition)* • *Callux joint field test network* • *2 seats in NOW advisory board*	• Relationships to politicians of network management • *Reputation and visibility as the biggest fuel cell & hydrogen network*		• Reputation and legitimization of VDI association

A further distinction depicted in this table is between organizational resources (regular) and *network resources* (italics, underlined), cf. section 4.5.1 for the details.

Source: Interviews

Structural resources were important to make the networks capable of work. All networks were based on governance structures such as specific rules and cultures (e.g. concerning membership, knowledge exchange) and modes of interaction (meetings, sub-committees etc). Here, organizational resources were used and network resources were established. In some networks, governance structures were developed and adapted over time and accomplished with trust and a joint understanding of goals, while in the case of Callux and VDI, sets of already established rules could be used or copied. The VDI, for instance, provided an established procedure which defines how a technical committee has to be set-up and proceed in order to publish a commonly accepted VDI guideline.

Relational resources included assets such as power and reputation. The reputation of associations (e.g. VDI and VDMA) and also of the new established networks has been described as a beneficial resource: the VDMA network operates with the VDMA association's reputation (e.g. as a credible and professional lobbying organization), and the technical committee can take along the VDI reputation and publish its joint work as a VDI guideline. Some networks, however, did not primarily rely on the reputation of their members. The IBZ fuel cell initiative, for example, developed and used its own reputation (network resource) as the competence center of stationary fuel cells. Power, as a resource of the network, originates from different sources. The constitution of the network members and their relationships to politicians were important organizational resources for the networks. Access to influential networks (e.g. Fuel Cell Alliance Germany) and seats in the influential governance structure of the National Innovation Program (NIP) Hydrogen and Fuel Cell Technology (e.g. NOW advisory board) have been mentioned here, for example to be useful in the implementation process of the NIP. These network resources were established while the network evolved.

The comparison of the five networks shows that they are well comparable in terms of financial and human resources. All networks operate on the basis of contributions by their members (firms and associations). There are also some similarities with regard to reputation that is transferred from member firms and the associations, which is involved in two cases. However, there are also differences among the networks. Some resources are very specific: trust, reputation and power are examples. This specificity is related to the fact that these resources were developed over some time – partly based on some of the other resources previously mentioned. Trust, for instance, has been developed while as certain members regularly met and achieved joint goals, accomplished by the governance structure of the networks.

The analysis of the portfolios also shows that the IBZ and the VDMA network develop much more network resources than the other networks. Most of them are related to the structural and relational category. The other networks do not develop many resources here but mostly rely on financial and human resources. The general pattern which evolves in the comparison is that for some networks, the organizational resources that are provided by the members play the key role whereas for other networks, the development and use of network resources is crucial. IBZ and VDMA are examples of the latter type.

These networks can manage a variety of tasks while they are deploying and combining resources at the network level. VDI and Callux, as examples of the former, draw on resources at the organizational level to fulfill particular tasks at the system level.

It seems that the kinds of resources used and created in the networks makes a difference, which is why, in the following, we take a closer look at two selected types.

4.4.2 Deployment of resources in the VDI and the IBZ cases

In this section, we take a closer look at how the different resources delineated in Table 8 were combined, altered and deployed in order to shape supportive structures at the system level. In addition, we differentiate the interplay of the different levels, i.e. how established system resources or contributed organizational resources have had an influence on the network. Due to space limitations, we can only report the results of two of the five networks. The VDI case was chosen because it represents a short-term to mid-term orientation network with a clear focus on one type of task: the development of technical guidelines. The IBZ case, in contrast, is a formal network with a mid- to long-term perspective to fulfill a series of system-building activities that also change over time. In Table 8, we have already observed that the latter network encompasses a broader range of resources to draw upon.

The case of the VDI technical committee

The main task of the VDI technical committee is the establishment of guidelines and technical norms for small scale cogeneration plants. Guidelines are important for market preparation of new technologies i.e. when service providers (e.g. fitters, architects) as well as fuel cell operators have to cope with high uncertainty, low level of transparency and information asymmetries. They make the achieved knowledge in the field explicit, define quality standards and also different kinds of operational procedures. As a result, the guidelines clarify the tasks which different actors (e.g. technology developers, fitters, fuel cell operators) have to pursue, and they also help to qualify downstream service providers.

In order to develop guidelines and to achieve the secondary goals, the VDI technical committee drew on financial resources (provided by the member firms) and on a series of experts, both from industrial players and research institutes. A crucial sub-task of the network was to integrate and formalize the distributed knowledge of the various experts. This ‘joint knowledge’ was a key ‘ingredient’ for the formulation of the guidelines. It can be interpreted as a resource that was not readily available but developed over time through the interaction of the individuals. Similarly, it was reported that a common understanding of the goals (and limits) of each guideline had to be established. There were also partly conflicting interests that had to be resolved. Of key importance for these processes of goal formulation and conflict resolution were the governance structures provided by the VDI association. These structures represent an organizational resource the association has built up over time. It is temporally shared with the different technical committees the association supports. Furthermore, during the guideline development process it became clear that software for the simulation of load profiles would be very helpful for applying a guideline in practice. For this end, data on reference load profiles were needed that could only be provided by electric utility companies. Finally, interviewees highlighted that the reputation of the VDI association was also essential to legitimate the guidelines.

Figure 8 depicts how the different resources were connected for the development of the guidelines (system level, in green). On the left, the different types of network members are listed. The arrows show which organizational resources the members have provided (in red). These direct resource inputs are then combined with those resources that developed over time within the network (blue color, in the middle of the box). The network boundary indicates on which resources the network can draw while influencing system resources.

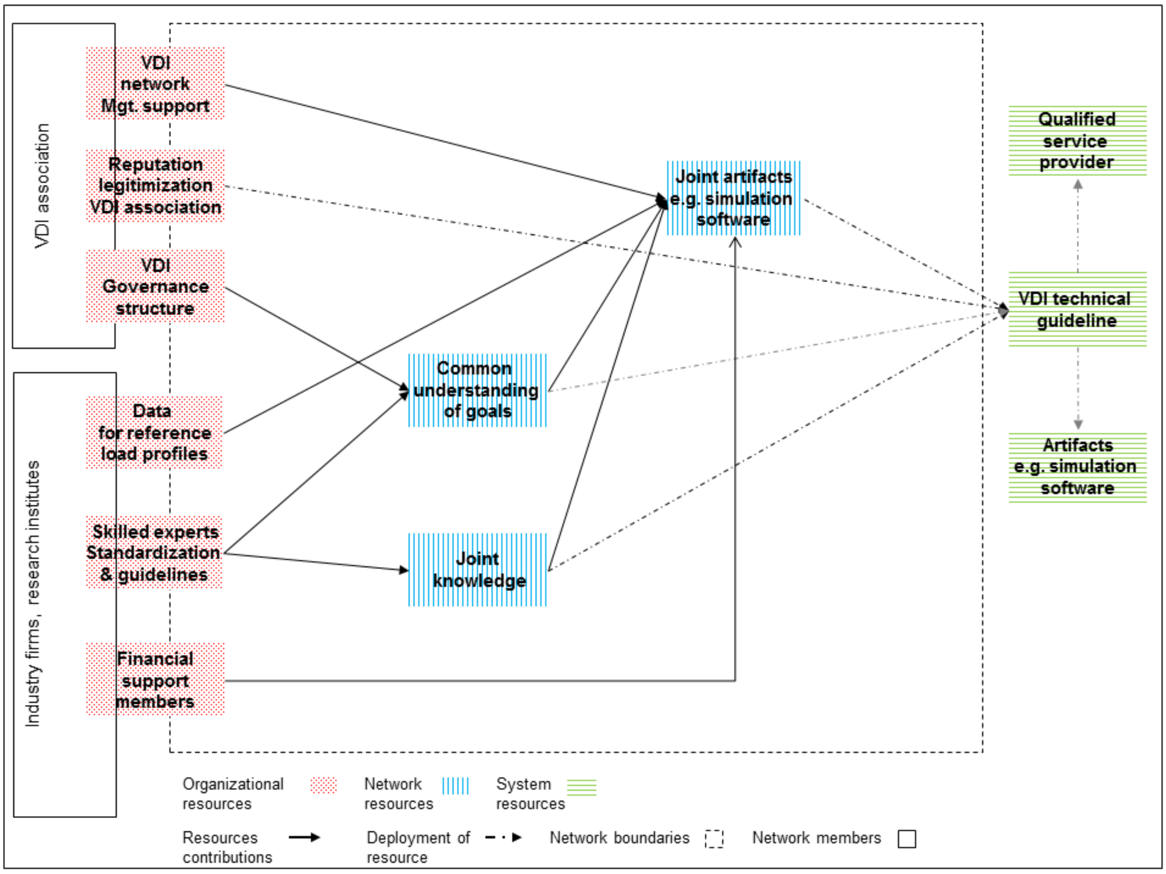

Figure 8: System-building in the case of the VDI technical committee

The diagram underlines that the VDI association played a particular role in the network as it provided pre-defined governance structures, a field-wide reputation as well as support for network management. In other words, the VDI provided its reputation and legitimation together with its experience in setting up guidelines, while the other members of the committee contributed to the content of the guidelines. Firms interested in market preparation, therefore, depended on the resources of the VDI association to develop guidelines. The case also shows that some organizational resources were altered to develop new resources at the network level (joint knowledge, common goals), while others such as VDI reputation are directly deployed towards the system level and the production and legitimating of guidelines. The establishment of guidelines at the system level had no effect on the resources at the network. In the IBZ case, however, established system resources also strengthened relational resources (e.g. power and reputation) of the network. We come back to this point in the next case.

The case of the IBZ fuel cell initiative

In contrast to the VDI technical committee, the IBZ fuel cell initiative has established and influenced a broad range of system resources. For example, the network shaped the awareness of stationary fuel cell technology, contributed to the qualification of service providers and also lobbied in favor of the National Innovation Program (NIP) Hydrogen and Fuel Cell Technology. Due to the complexity of the IBZ example, we only discuss the manipulation of three system resources in the following: awareness, collective expectations on stationary fuel cells and the NIP support program. Again, the idea is to show how the network depended on different kinds of resources to accomplish its tasks.

One reason to found the IBZ was that a hype on fuel cell technology occurred around 2001 (Ruef and Markard, 2010). It became increasingly clear that the promises which many firms had given to position themselves for the expected competitive race could not be fulfilled. Through the IBZ fuel cells initiative, therefore, some leading firms decided to coordinate their PR and communication efforts and to present a more realistic picture of fuel cell technology in the public (i.e. to manage collective expectations). While these firms had technological expertise as well as financial resources at their disposal, the more crucial resources needed to achieve this goal were a common understanding and internal rules of how to agree on possibly conflictive issues (governance structures). These resources were created through the foundation of a steering committee, in addition to the close interaction of network members. In addition to that, more ‘practical’ resources such as the IBZ web page, a newsletter-letter, info-CDs, an information hotline, joint booths at trade fairs and IBZ press releases were developed. These joint artifacts for PR and communication were directly deployed to influence the awareness, image and collective expectations on stationary fuel cells. However, in order to be more effective, the IBZ fuel cells initiative also worked on building up a reputation. This went hand in hand with the communication efforts and also depended on the expertise and joint knowledge of the network. Today, the IBZ has a renowned standing as the competence center for stationary fuel cells in Germany. This reputation is a valuable resource that can be deployed for a broad range of purposes. Finally, it was reported that trust among the IBZ members increased over time, resulting in a case of escalated commitment (Wijen and Ansari, 2007): a key member could convince the less committed IBZ firms to start the joint field test Callux to increase visibility, and additionally influence public awareness. As a consequence, the network became more and more stable and was able to take over new and even more complex tasks. One of these new tasks was lobbying in favor of the NIP support program.

For the manipulation of the NIP support program, the IBZ could deploy its power and influence as key network in the field of stationary fuel cells. This resource at the network level is based on the power contributed by IBZ members, but was further accomplished through the accumulated reputation as a competence center of stationary fuel cells. Joint knowledge and expertise, in addition to the access to the Fuel Cell Alliance Germany, supported the network to exert its influence in the establishment process of NIP, NEP, and NOW (cf. section 4.3). Interestingly, the establishment of the NIP support program and the subsequent new governance structures (e.g. NOW advisory board) also increased the quality of the relational resources of the IBZ. The power and reputation of the network were strengthened through the establishment of system resources. Through the NOW advisory board IBZ network can exert power and influence both the NIP implementation and the NEP adaption (c.f. section 4.3).

Figure 9 depicts the different kinds of resources the IBZ relies on. Financial resources, skilled experts, and power and relationships to politicians are provided by the member firms and an association. These inputs are transformed into network resources (blue boxes), which then are used towards the creation and shaping of system resources (green boxes, right side). The IBZ combines and deploys organizational resources to create a range of new ones, which are used for multiple purposes. Of particular importance here are common goals, trust among network members and the reputation of the network. Notably, the interviewees not only reported the relevance of these network specific resources but also mentioned that they are deliberately strengthened (e.g. reputation is enhanced through targeted communication and 'networking' activities).

Due to the key role of network resources, the IBZ did not to a great extent depend on the resources of specific members. The inputs, in other words, were not very specific but the resources that were developed on the basis of these inputs are very unique, influential and inseparably linked to the network. Relational resources such as power and reputation in particular seemed to play a key role in system-building and the creation and change of supportive institutions. However, it took time to develop these specific network resources, which is why the IBZ was rather weak at the beginning and only became influential over time.

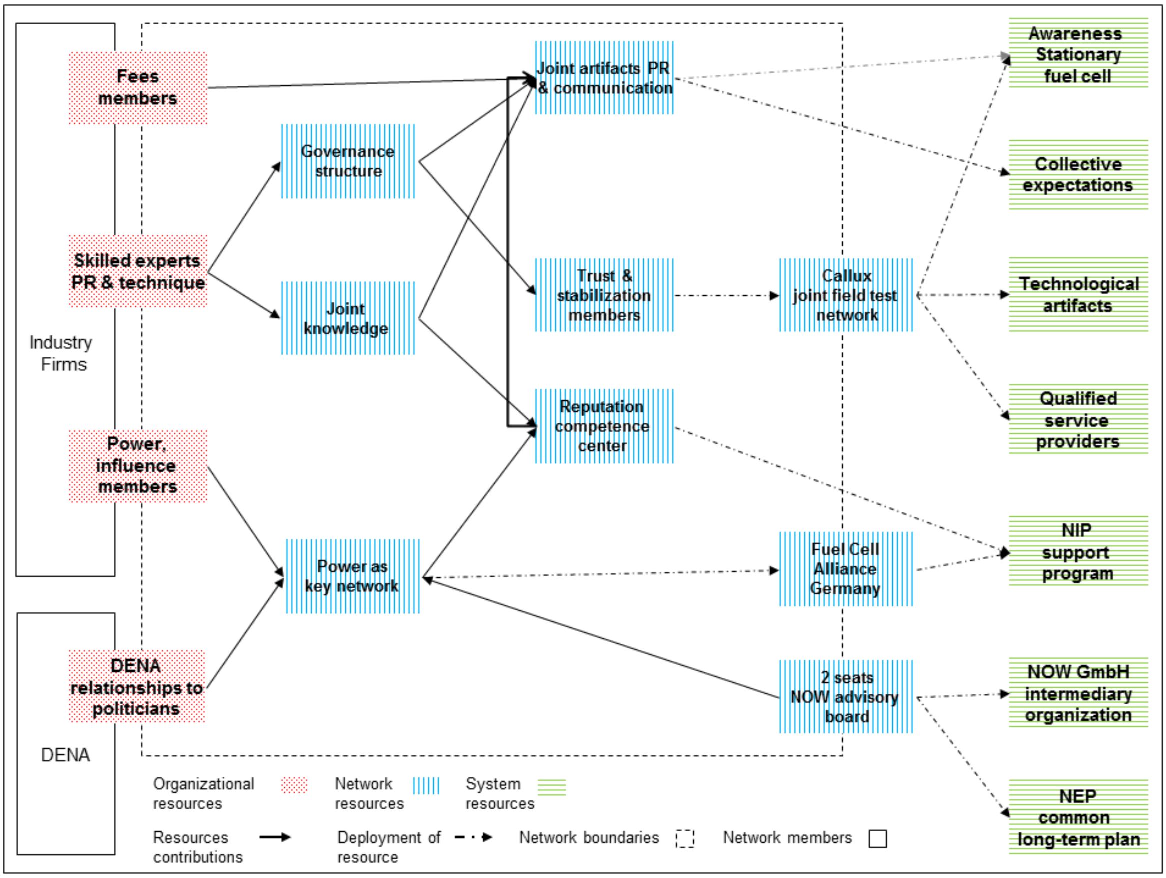

Figure 9: System-building in the IBZ case

The comparison of IBZ and VDI shows the IBZ has many more network resources at its disposal. A network which draws on network resources may combine a variety of them to influence a broad range of system resources, whereas a network which draws on organizational resources is constrained in its resource combination and deployment at the system level. In addition to this, in the IBZ case the quality of some network resources was increased through the establishment of complementary system resources (e.g. NIP governance structure), while in the case of the VDI network these effects were not studied. Both networks can also be differentiated according to how they obtained these resources. In the IBZ case network members were strategically accumulating and creating resources at the network level, while in the case of the VDI the technical committee had to couple with an established organization to get access to essential resources.[34] For the latter network, the associations still decide on which purpose the resources are deployed. That is also true for the IBZ, but as the network draws mainly on network resources, the IBZ can control the deployment of this type of resource.

[34] Therefore the description of the IBZ case has the character of a time observation of the actual system building capacity of the network, whereas the course of action to produce guidelines in the VDI case is rather stable.

Resources at the organizational and network level have different properties. In the next section we summarize and specify the identified resources, and discuss how the identified network types differ in their ability to create and shape a TIS.

4.5 Differentiation of resources and networks in system-building

Our results have shown that the five networks used different kinds of resources to achieve their goals. In this section, we compare the characteristics of organizational- and network resources and discuss how they affect the system-building capacity of formal networks.

4.5.1 Comparison of organizational resource and network resources

Formal networks develop and use resources to achieve their strategic goals, in a similar way to firms and other organizations. In our study we identified two kinds of resource deployed by the networks. Firstly, all networks relied on organizational resources provided by their members. These were either transferred into the network as in the case of financial resources, or they remained 'attached' and under the control of the members while they were used within the network. Examples for the latter include the reputation, the political contacts of members or the experts employed by members. We will refer to these resources as *organizational resources of network members*. Secondly, the networks also relied on resources that were developed over time within the network. Examples of network resources encompass trust among members, network culture, a common understanding of goals, a specific mode of network governance and the reputation of a network. We refer to them as *network resources* with the following definition:

> Network resources are assets of a formal network that are of strategic value for network members. They are generated through the interplay of actors and their organizational resources in the network.

Table 8 lists the firm and network resources that were used for system-building by the five networks in our study. Organizational resources of network members and network resources have different properties. We compare where they are created, when they become available for the network, how they are controlled and which advantages can be expected with regard to system-building (cf. Table 9).

Organizational resources of network members become available at the network level if a firm, for example, joins the network and decides to grant others access to some of its resources. The member still owns and controls these resources, and it might also decide to withdraw them again. With regard to system-building, organizational resources have the advantage that they come with the members, i.e. they are typically available as soon as a member joins. A disadvantage is that in order to achieve particular system-building tasks, specific members (and their resources) may be needed, which creates a certain dependency and limitation in system-building. Take for example the VDI association with its resources for the development of technical norms (Figure 8). If it had not participated, the set-up of common guidelines would probably have been much more difficult.

Network resources are generated and accumulated over time through the interplay of network members. As a consequence they are not readily available when the network is set up. The creation of network resources may be a deliberate act (e.g. establishment and adaptation of the governance structure in the IBZ), but they may also emerge in a less planned way (e.g. trust among members, reputation of the network), which means that their nature and benefits are not necessarily clear in the beginning. Network resources are controlled by 'the network', i.e. they can be deployed, developed further or changed where the network members see fit. Ideally they can be continuously adapted to the needs of the network. Some network resources such as its reputation may also be of more general use, i.e. they can be deployed for a broad range of tasks.

Table 9: Properties of organizational resources of networks and network resources

	Organizational resources of network members	**Network resources**
Creation	Created at the firm level; creation is typically independent of the processes at the network level	Created within the network, e.g. through the interaction of network members
Availability	Often directly available when an organization joins the network (e.g. when the network is established)	Might take time to develop, availability delayed
Control	Controlled by members, resource access may be withdrawn (e.g. through exit)	Not under the control of single members, access cannot be withdrawn, network can further maintain and modify the resource
Advantages and disadvantages with regard to system-building	Resource can be directly deployed to a specific task; system-building capacity might be constrained	Resource can be tailored and maintained in favor of multiple system-building tasks; system-building capacity have to be developed

Source: own depiction

The identified resource types are instrumental to detect the importance of different networks in system-building i.e. what kinds of tasks the networks can achieve. In the following we discuss different types of networks, depending on which types of resources they typically develop and deploy.

4.5.2 Discussion of the importance of different networks for system-building

Our empirical analysis has also shown that different networks play different roles in the formation of an innovation system, and they depend on different kinds of resources to achieve their goals. Some networks rely mainly on the resources of their members, while others develop a broad range of network resources. The IBZ, for example, combines a variety of network resources to influence major system resources such as the National Innovation Program. The VDI committee, in contrast, relies primarily on organizational resources and uses just a few network resources to develop guidelines. This task is rather specific, and was reported to be less complex than setting up and managing the aforementioned innovation program.

In Table 10 we conceptually compare two different types of networks: those drawing primarily on organizational resources and those that deploy a broad range of network resources.

Networks can be based on established organizations and use primarily the resources already available in these organizations. The underlying strategy is to identify complementary resources of different actors, to combine these resources (through the membership of the actors that control them) in a network and to apply them directly towards the network goals. This is how a member of the VDI technical committee described it:

> "In order to better organize their interests [in market preparation], they [industry firms] joined forces in the technical committee of fuel cells for domestic homes, and started to explore the possibilities offered by the VDI association for the market preparation of stationary fuel cells. If you look at the field of activity [..] the VDI is strong in the creation of guidelines which are not obligatory, but so secure in terms of technology that they are convertible for all applications. The set-up of technologically high quality guidelines is what the VDI does particularly well."

Such networks might remain constrained in what they can achieve at the system level. The challenge is that they strongly depend on the resources provided by their members. Organizational resources available at the network level cannot be freely combined, leveraged and deployed. As a result, such networks may only be able to create and shape some specific system resources, while there may be other tasks at the system level they cannot fulfill.[35]

Networks, which extensively draw on network resources, have advantages in the case of complex system-building tasks. Their underlying strategy is based on the development and accumulation of network resources. They are less constrained as they can combine and deploy different network resources for different tasks. Some influential members might even see new valuable resource combinations, and steer the networks towards new system-building goals. In other words, these networks may evolve (in a co-evolutionary manner) in relation to the tasks or problems which appear as the technology matures, or as one member of the IBZ has stated:

> "We did not start out in 2001 with the aim to achieve A, B, C and D in certain way. The requirements of the IBZ have changed and have developed […]. I think the cool thing about IBZ is that the network has to continuously to renew itself, to continuously reinvent itself. And I believe that the secret of success of

[35] To give an example, in the case of VDI technical committee, market entry barriers in the area of apartment houses came onto the agenda: as tenants in apartment houses could choose their energy service provider in a liberalized market, landlords would not install decentralized CHP technologies. However, as soon as it became clear that this was a political topic (related to the billing of energy costs), the members of the technical committee realized that they could not work towards solutions within the structures of the VDI network.

a good network is its continuous renewal, and that's why we can actually say: that is the point where IBZ is currently standing."

These kinds of networks are multi-task oriented and may be able to create a broad range of system resources, as well as addressing very complex and challenging tasks at the system level.[36]

Table 10: Comparison of two different types of networks

	Networks drawing primarily on organizational resources	Networks drawing extensively on network resources
Key resource type	Organizational resources of members	Network resources
Underlying strategy	Identification and combination of complementary resources of network members for specific tasks	Development & accumulation of network resources to extent system-building capacity
Resource combination & deployment	Constrained, resources under control of network members	Rather flexible & adaptable, key resources under the control of the network
Influence at system level	Single task oriented: networks influence rather specific and towards not very complex system resources	Multi tasks oriented: networks influence rather systemic towards complex system resources
Relevance for members	Limited ability to adapt to future needs of members, often do not represent key network in TIS	Adaptable to future needs of members, network may play a key role in TIS formation

Source: own depiction

Finally, both types of networks can be differentiated in their relevance for their members. The latter type has a long-term perspective, develops and combines various resources, and can adapt to the future needs of members and emerging tasks in the TIS build-up. In addition, the quality of the resources at its disposal (e.g. reputation and power) may even increase as the system and its structural elements evolve. That is why they also play a key role for their members. Single task networks in contrast, are more constrained in their adaption to the future needs of the members. The quality of their main organizational resources is rather unaffected by structural TIS build-up.

[36] If these networks also have a long term perspective, there might be some learning effects in system building, and they may develop specific capabilities to fulfill TIS build-up tasks more effectively.

4.6 Summary and outlook

In this paper, we have been studying *why networks differ in their abilities to influence system resources* and *which kinds of formal networks might be important for the build-up process of an emerging TIS*. Formal networks rely on different bundles of resources, which explain why the networks can take over different tasks in terms of system-building. On the one hand, networks use and combine the organizational resources of their members: financial resources, expertise, firm reputation etc. On the other hand, new intangible resources emerge at the network level including specific governance structures, a common understanding of the strategic goals, trust among network members or the reputation of the network. While both types of resources were necessary for system-building, our analysis showed that network resources are not readily available when a network is set up but need time to develop. Once established, they can become quite important for achieving the network goals. Moreover, they can often be applied to a broad variety of tasks. Through the development of network resources a formal network may become more influential and powerful over time, even if the organizational resources provided by the network members do not change a lot.

On the basis of these differences in resources, we suggested to distinguish two types of formal networks: those that rely primarily on the organizational resources of network members, and those that build extensively on network resources.[37] In the fuel cell TIS, the former were used for specific system-building tasks, which were easily comprehensible and of a defined scope, and the latter were applied in situations where system-building was more complex and the tasks less foreseeable and manageable. The flexibility of the second type of networks and their ability to address multiple tasks were crucial for successful system-building in this case. The IBZ fuel cell initiative, for example, was reported as being crucial in the competition of different fuel cell applications and for the formation of the TIS for stationary fuel cells in Germany. Without the network, influential system resources such as the National Innovation Program might not have been modified in favour of stationary fuel cells.

As a consequence, networks that draw extensively on network resources may also turn out to play an essential role in other emerging technological fields, especially when compared with networks which are primarily based on organizational resources. In addition, networks with a long-term perspective may also accumulate important relational resources (e.g. power, reputation), which again make them less dependent on the contributions of their members.

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[37] We must acknowledge that the delineated networks are ideal types in a continuum of different formal networks in TIS.

4.6.1 Contributions to TIS concept

This study has developed a differentiated perspective on the role of resources in technological innovation systems. While earlier studies have already pointed to the importance of resource mobilization for successful technology development (Bergek et al., 2008a, Hekkert et al., 2007), the resource concept remained very general and the underlying processes did not receive much attention. Our framework makes at least three improvements here: firstly, it directs our attention to processes of resource creation and transformation. Resources that are crucial for the technology at hand are often specific and not readily available, which is why they have to be developed over time. The strategies of different actors and formal networks play an important role in this regard (Farla et al., 2012; Markard and Truffer, 2008a). Secondly, our framework points to the strategic value of resources for the actors in an innovation system. This is in line with the original ideas of resource-based reasoning in the strategic management literature (Barney, 1991; Dierickx and Cool, 1989). Our particular focus was on the strategic value of resources for system-building, but the resource concept could have also been applied to other processes in innovation systems, e.g. to the competition between different technological variants for public funding. A crucial benefit for TIS studies is that the resource concept can be used to explain the strategies of organizations in technological innovation systems (Markard et al. 2011). Thirdly, we distinguished resources at different levels of aggregation, i.e. resources at the organizational level, network resources at the level of formal networks, and system resources at the TIS level. This differentiation was particularly helpful to explain the transformation of resources. In the IBZ network, for example, expertise, financial resources and personal contacts of member firms were the basis on which the reputation, political influence and trust of the network grew, which finally enabled the development of system resources such as the Callux field test platform and the NIP support program.

Another major contribution is related to how we conceptualize networks in technological innovation systems. So far, they have been primarily regarded as (informal) structures that facilitate knowledge exchange (Carlsson and Stankiewicz, 1991; Chang and Chen, 2004) or expand the resource base of individual firms (Jacobsson and Johnson, 2000; Gulati, 1999). Our framework extends this view, as it points to the role of (formal) networks as organizational structures: formal networks can be conceptualized as a source of agency, as entities which control and accumulate different kinds of resources as well as pursuing specific strategies, e.g. in terms of system-building.

We believe that these new perspectives are of general value for innovation studies. In this chapter we have applied them specifically to the issue of innovation system-building, resulting in a threefold contribution: Firstly, our approach highlights the strategic nature of system-building with a deliberate deployment of resources at different levels. This complements the view that system formation is largely an emergent process without much coordinated action. In general, system-building has received rather little attention in the TIS literature until now. Our analysis shows that system-building was initiated with actors identifying deficits in the technological field (e.g. ill-defined interfaces between components of a product, missing skilled fitters) and joining forces in formal networks to develop structures that help to improve the situation (e.g. technical norms, educational programs). In these networks, they used different sets of existing organizational resources but they also developed new resources and competences at the network level. These network resources often take time to build up, which means that the range of tasks a network can fulfill increases as network resources are accumulated and established.[38] In situations where different innovative technologies compete for public support, some network resources can be expected to be central for system-building.

Secondly, the resource concept helps to analyze the role of different actors and networks for system-building. While TIS scholars have regularly pointed to the pivotal role of prime movers (Jacobsson and Johnson, 2000), there was little conceptual explanation for what differentiates a key actor or system builder from a more peripheral actor. Resource-based reasoning highlights that organizations possess different resources and that some of these resources may be unique and difficult to substitute (Barney, 1991; Dierickx and Cool, 1989). While we were studying processes at the network level, it became obvious that specific resource contributions by the network members were essential to accomplish the aims of the network. These members represent a difficult-to-substitute key actor for a specific system-building task: without their procedural competences and resources, the development of certain system resources would be difficult (e.g. the VDI case). Formal networks can be differentiated in a similar way with regard to their importance for the TIS. Networks have different sets of resources, i.e. organizational resources and network resources, which they can deploy for system-building. An analysis of the resource and competence base of different networks can therefore be key in the assessment of their system-building capacity. It has to be noted, though, that this resource portfolio will change over time (and thus the role of the network).

Thirdly, we have directed attention to the interplay of firm, network and system level processes thus contributing to the broader research agenda on micro-level dynamics in broader socio-technical transformations (Farla et al., 2012; Markard et al., 2011; Musiolik and Markard, 2012). Take the interplay of resources at different levels: as attractive system resources are developed, new actors enter the innovation system, which possibly makes new and complementary organizational resources available. While studying

[38] These findings correspond with a model developed in the RBV literature (Dierickx and Cool, 1989). In the model, a stock of accumulated assets determines what a firm can actually do, while a flow of assets leads to a higher level of strategic opportunities. This flow of assets is rather planned and steered. This might also holds true for key innovation networks in TIS, in which key members of the networks strategically steer the development of resources and capacities in system building.

networks, we not only got a better understanding of how resources are established, combined and finally deployed for system-building, but also of the interplay between these levels. In a similar vein, we saw that a newly created system resource, the governance structure of the NIP, had a positive feed-back on the reputation of the IBZ network. Through these feed-backs, cumulative effects may be triggered which are crucial for the dynamics we observe in many technological fields (Suurs and Hekkert, 2009).

4.6.2 Limitations and future research

The present study clearly has its limitations with regard to the generalization of its results. We have analyzed a specific TIS in a defined national setting with a selected set of formal networks. While it seems to be plausible that some of the aforementioned observations and conceptualizations can be transferred to other cases, this remains to be tested in further studies with a similar research design. For example, German industries are known for the typically strong role played by formal networks and associations (Vasudeva, 2009). In other countries, we might identify network structures that differ from those presented before. Still, we believe that similar approaches to coordinate different kinds of actors can be found.

Today, we are just beginning to understand the particularities of the strategic moves of firms and system-building (Konrad et al., 2012; Musiolik and Markard, 2011). The use of resource based reasoning, and the integration of the resource concept in TIS, thus opens up possibilities for conceptually incorporating strategic decision-making at the firm level into the development process of a TIS. So far, we have concentrated on co-operative strategies directed at system-building. However, we can additionally expect groups of firms and networks to compete in the development of system resources, especially if these resources provide very different benefits for different constituencies (Musiolik, 2011). Further research may follow up on these issues, thus providing additional insights into the maneuvers and strategies of firms and other actors in emerging technological fields.

Future studies may also shed light on the obstacles of collective action in the presence of ambiguity. Ill-functioning networks can be analyzed, for example, with regard to what hampers the development of critical resources at the network level. Network formation may be hindered because potential network members are afraid of ‘giving away’ valuable organizational resources. Alternatively, there might even be too much network formation. In the case of fuel cells, politicians as well as firms became confused during the hype in 2001 and the subsequent disappointment (Konrad et al., 2012; Ruef and Markard, 2010). The hype was accompanied by an uncoordinated emergence of networks, and a manifold articulation of needs and expectations. Both the coordination and structuring of the network activities and the development of an overall governance structure (at the system level) became very important, and could, finally, be achieved through the coordinated activities of leading actors in the field. Therefore, a better understanding of the underlying social processes and of leadership in networks is also needed. Future studies may follow up on this issue as they analyze how system builders (Hughes, 1979) steer and guide the development of TIS. Findings from the entrepreneurship literature might be a promising starting point in this regard (Sarasvathy, 2001, 2008; Sarasvathy and Dew, 2005).[39]

These examples for future research will not only increase our understanding of system-building, i.e. the interplay of strategic action and technology development at the innovation system level but it will also contribute to the even broader research agenda on socio-technical transitions towards more sustainable modes of production and consumption (Markard et al., 2012).

[39] According to this perspective another level of analysis has also been taken into account: the intra-firm context and the internal resources and networks of a firm´s business unit. Especially system builders or champions (Howell and Higgins, 1990) within big firms have to draw on internal resources of their business units to secure their activities in technology entrepreneurship. It was already evident in our interviews that achievements at the TIS level (e.g. creation of NIP support program) also had an impact on 'the standing' of fuel cell business units of the manufacturers studied. Activities within firms, formal networks and at the level of the TIS are thus interlinked.

Interlude chapter 5

The success of radical technologies depends highly on the establishment of supportive structures (e.g. standards, R&D programs) as parts of a larger technological innovation system. In this chapter we review system-building in the literature and analyze 7 cases of system-building in the field of stationary fuel cells. Drawing on a framework which conceptualizes system-building as a transformation of resources at different levels, we identify five modes system builders have used to organize system-building processes. In the prime mover mode, a powerful actor deploys its organizational resources to directly create supportive structures at the system level. The alliance mode evolves when resources are distributed and a system builder has to involve partners to co-create a system resource. In the orchestrated mode, a system builder steers joint activities and the development and usage of resources in networks. In the coalition mode, system builders cooperate and deploy an advocacy coalition towards system resource formation. Finally, in the intermediary mode, key system builders create an intermediary organization, which then manages TIS development. We conclude that strategic system-building depends on how resources are distributed among innovating actors and whether the required resources are already available or have to be developed first.

5 Technology innovation and strategic system-building: the case of stationary fuel cells

5.1 Introduction

Today decentralized or distributed technologies play a key role in the transition of the current electricity system towards greater sustainability. Despite their potential, distributed technologies such as photovoltaics or stationary fuel cells still only account for a small percentage of the overall electricity supply, while conventional, centralized power plants remain central (De Vries et al., 2007; Hoogwijk, 2004; Rogner, 2000). Distributed technologies are radically different from the dominant mode of central energy generation (and the underlying technological paradigm) and their diffusion requires substantial changes on the supply side (how manufacturers, suppliers, research institutes etc. interact), as well as the user side (Geels et al., 2004). For technologies in a rather early stage of development, the step from prototypes or small batch products to mass production is very critical. They face several interrelated problems as markets and value chains are not easily formed. Innovating firms cannot build on established routines, standards, suppliers, services and maintenance structures on the supply side, nor can they rely on interested customers and developed distribution channels on the user side. In fact radical innovations do not just depend on the development of a technology or prototype, but also on the establishment of a wider social-technical system or technological field in which the innovation can be embedded (Garud and Karnoe, 2003; Van de Ven, 1993; Van de Ven and Garud, 1989).

Such a supportive socio-technical system can neither be taken for granted nor treated as external to the innovation process. Instead it has to be built up purposefully. In the innovation studies literature, so-called system builders or prime movers have been identified as they shape and create supportive structures and turn them into a socio-technical system of interacting components (Hughes, 1979; Ylinenpaa, 2009). System-building and the establishment of technological fields play a key role in sustainability transitions and the development of clean technologies (Markard et al., 2012). Under such circumstances, innovation strategy at the firm level is not so much about positioning in already existing markets, but it is about exploring and developing value creating systems (Ramirez, 1999) and the co-creation of new markets (Sarasvathy and Dew, 2005). The development of new technological fields is therefore a complex process which depends on coordination, collective action and the commitment of complementary actors. Innovating actors follow a system-building approach as they intentionally set up business networks, value creating systems and broader (institutional) structures to realize new business opportunities (Hajek et al., 2011). How innovating actors proceed in system-building and what kinds of typical strategies and resources they deploy to initiate and steer the build-up of supportive socio-technical systems, however, has not yet been studied in the literature.

The process of system-building can be explored with the help of the literature on technological innovation systems (Carlsson et al., 2002b; Markard and Truffer, 2008b). Technological innovation systems consist of structural components such as actors, institutions and networks which interact and contribute to the generation, utilization, and diffusion of a specific technology (Carlsson and Stankiewicz, 1991). System components such as common standards, specific R&D programs or collective expectations can provide positive externalities as they guide the search and reduce uncertainties, for example. Therefore, they are often strategically created and shaped by innovating actors (Garud et al., 2002; Musiolik and Markard, 2011). While the TIS approach has been mainly used to analyze interdependences of structural components and system dynamics (Bergek et al., 2008a; Jacobsson and Bergek, 2004) we focus in particular on deliberate activities of system builders, key persons and organizations, which realize strategies and deliberately contribute to the formation of system structures (Hellsmark and Jacobsson, 2009; Hughes, 1979).

Our understanding of system-building departs from the TIS framework, incorporates ideas of Sarasvathy and colleagues (Sarasvathy and Dew, 2005; Wiltbank et al., 2006), and draws in particular on the concept of resources (Barney, 1991; Dyer and Singh, 1998). We develop a model of resource-driven TIS build-up, in which innovating actors follow a system-building strategy: they create and shape supportive system elements, which provide externalities, facilitate innovation, and harness the commitment of complementary actors. To do so, system builders start from the resources they have at their disposal and successively involve other actors to increase the available resources. This strategy – forging networks of actors and setting up a cycle which increases the resources available – reduces ambiguity and uncertainty as a technological field is co-created (Sarasvathy and Dew, 2005; Wiltbank et al., 2006).[40] System builders identify, develop, and deploy resources at the organizational, network, and system level in order to build-up a supportive TIS and to increase the prospects of the new technology.

In this research, we followed up on earlier findings on the TIS of stationary fuel cells in Germany (Musiolik and Markard, 2011; Musiolik et al., 2012) and conducted interviews with key actors that were engaged in system-building activities. The results of our study provide insights into the process of deliberate system-building and reveal the modes typically used by system builders. Knowledge of these modes is especially important for politicians who might want to support system builders, e.g. to foster a rapid market

[40] Ambiguity is defined as the lack of clarity about the meaning and implications of particular events or situations (Santos and Eisenhardt, 2009). It arises from a lack of recurrent, institutionalized patterns of relations and actions.

introduction of clean technologies, as well as for managers of technology firms who need to understand and assess viable system-building strategies.

The rest of this chapteris structured as follows: Section 5.2 reviews the TIS literature and the literature on system-building and introduces key dimensions of a resources-driven system-building. Section 5.3 discusses the methodology used in this study. Sections 5.4 and 5.5 present the results from different system-building cases, delineate typical modes of system-building, and compare their dependencies on specific resources and skills. Section 5.6 concludes.

5.2 Theoretical perspectives on system-building

In this section we introduce the TIS concept, discuss its limitations and review and summarize the related literature on system-building. Finally, we introduce our conceptual starting point of resources-driven system-building.

5.2.1 Technological innovation systems framework and its view on system-building

For the study of emergent technological fields, the concept of technological innovation systems (TIS) is particularly useful. A TIS can be defined as 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" (Markard and Truffer, 2008b, 611). The concept derives from idea that technology innovation is both: an individual and collective act. Determinants of innovation reside not only in individual firms but are also embedded in the wider innovation system which supports, guides and also constrains the activities of individual actors (Jacobsson and Bergek, 2004).

A TIS consists of system components such as actors, institutions and technology and the various relationships among them (Carlsson et al., 2002b). Actors include firms, research institutes, industry associations, banks or public authorities. Networks of actors determine the transfer of knowledge and other resources, but also provide organizational structures for collective action (Musiolik et al., 2012). Institutional infrastructure encompasses technology-specific norms, laws, regulations, guidelines, values, culture, cognitive frames, and collective expectations.[41] Technology, finally, subsumes artifacts such as tools, plants, machines, but also knowledge embodied in patents or engineers and scientists. It is both a structural element but also an output of the system (Bergek et al., 2008b).

Early TIS studies focused on system structures while later work has used functional analysis to evaluate the actual performance of a TIS (e.g. Bergek et al., 2008a; Hekkert et

[41] Institutions influence the activities and decisions of the actors, and they enable, but also constrain, action.

al., 2007; Suurs and Hekkert, 2009). Structures and key processes which support or hamper the development of a particular technology have been analyzed in empirical studies and evaluated to inform decision makers (Hekkert et al., 2007; Negro et al., 2007; Negro et al., 2008; Suurs and Hekkert, 2009).

The process of system-building is studied in the TIS literature and also reflected in the system functions, e.g. market formation. In most studies, however, TIS formation is understood as an emergent process resulting from the various, largely uncoordinated activities of system actors. As firms and other organizations 'enter' a TIS, knowledge and artifacts accumulate, networks become established and institutional structures align, which results in the provisioning of positive externalities (Bergek et al., 2008a; Hekkert et al., 2007; Suurs and Hekkert, 2009). In other words, free utilities emerge as side effects of an accumulation of actors and 'critical mass'. The same holds true for the emergence of specific labor markets, service providers or knowledge spill-overs, which are also explained by an enlargement of the actor base or co-location effects (ibid). While this understanding of system-building has to be appreciated, we think it misses strategic action and the pursuit of different interests in emerging technological fields. In the innovation systems literature, little attention has been paid to processes, in which innovation systems are also deliberately shaped and created (Musiolik and Markard, 2011). As the structures of technological innovation systems represent valuable resources for innovating firms (ibid), we expect that firms and other organizations have a strategic interest in how these structures look like.

While strategic maneuvering certainly takes place in all stages of the development of technological fields, it is probably in the early phase, when system-building can be studied best. It is also acknowledged in the literature, that the early, pre-formative phase of TIS, in which first structures and the interplay of different actors evolve, is still poorly understood (cf. Jacobsson and Bergek, 2004; Nygaard, 2008).

To sum up, the TIS literature so far has a rather narrow perspective on innovation system-building. Through the entry of actors and the mobilization of resources, innovation systems emerge in a quasi-natural way and subsequently generate positive externalities. Other streams of literature, in contrast, have a more explicit focus on system-building and the role of system builders in radical innovation. Here system-building is explained by the efforts of capable system builders or analyzed by specific concepts such as path creation and interactive emergence.

5.2.2 System-building in other strands of literature

System-building has been part of different streams of literature. In the following we review selected contributions of the literature on large technical systems (Hughes, 1987), the social construction of technology (Garud and Karnoe, 2003), the creation of new business fields (Lundgren, 1995; Möller, 2010) and entrepreneurship (Sarasvathy and Dew, 2005; Wiltbank et al., 2006).[42] While doing so we emphasize different contributions to the concept of system-building and also differentiate the approaches according to the concept of agency and coordination used.

The literature on large technical systems (LTS) highlights the role of central actors, e.g. entrepreneurs such as Edison for system-building (Hughes, 1979; Hughes, 1986; Law, 1987). These genius entrepreneurs were not only concerned with the development of technical artifacts but also with the necessary complementary organizational and institutional structures such as manufacturing firms, utility companies, academic research, investment banks or technological standards. These different components make up a system as they interact functionally to fulfill a common goal. Following these ideas, system-building is about central actors who have the skills to realize their visions and to coordinate and build-up "a world where bits and pieces, social, natural, physical and economic are interrelated" (Law, 1987).[43] In this model, agency is assigned to a few system builders, who have all abilities to discover, create and exploit new business opportunities.

The literature on the social construction of technology (SCOT) addresses the role of (distributed) human agency in shaping technologies (Bijker et al., 1987; Callon, 1987). Advocates argue that technology entrepreneurship and the creation of new opportunities builds upon the efforts of many and cannot be devoted to a single entrepreneur. Instead concepts such as 'distributed agency' or the metaphor of innovators who 'run in packs' are used to explain coordination and the emergence of a new field (Garud and Karnoe, 2003; Van de Ven, 2005).[44] In particular the process of interactive emergence is central and the idea of path creation introduced to explain system-building (Garud and Karnoe, 2003;

[42] Different streams of literature provide similar concepts (or labels) to the idea of TIS such as 'large technical systems' (Hughes, 1987), 'technological fields' or 'social systems' (Garud and Karnoe, 2003; Van de Ven and Garud, 1989) or 'social-technical regimes' (Geels, 2002; Geels, 2005), industry clusters (Porter, 1998) and business fields (Lundgren, 1995; Möller, 2010). While we acknowledge that these concepts are not the same, we think they are similar enough to draw on the various insights provided by these literatures.

[43] Components in a system have to interact harmoniously, and are interrelated with characteristics of others. They permanently interact and changes in one component lead to influences at another side of the system. System builders take this into account. If existing artifacts and organizations are to be used, then they must be transformed (Callon, 1980; Hughes, 1986).

[44] The outcomes of strategic actions cannot be attributed to any single entrepreneur, and therefore interactive emergence stands in contrast to the traditional view on strategy and the "design school" (Mintzberg, 1999).

Garud and Karnøe, 2001; Van de Ven and Garud, 1989).[45] In a comparative study of the emergence of the Danish and US wind turbine industry, Garud and Karnoe (2003) differentiated two approaches for path creation: *bricolage* and *breakthrough*, and concluded that agency is not only distributed between actors but also embedded: inputs of a multiplicity of actors such as producers, users, evaluators and regulators result in a steady accumulation of artifacts, tools, practices, knowledge and thus coordinate (constraints) further action (Garud and Karnoe, 2003; Latour, 1991).[46]

The literature on the construction of new business fields investigates how new business opportunities are created and shaped (Lundgren, 1995; Möller, 2010; Normann and Ramirez, 1993).[47] The business emergence process is key and has been explained by three parallel but interrelated phases: exploration of future business opportunities, mobilization for design, and applications and mobilization for dissemination (Anderson and Tushman, 1990; Lundgren, 1995; Möller, 2010). For some authors the emergence of new business networks is rather uncoordinated without 'great design strategies' (Lundgren, 1995) while other authors try to explain how actors are creating and shaping business opportunities, e.g. through sense making or agenda construction (Möller, 2010). In addition, market creation does not merely depend on complementary activities in business networks (or value chains) but also on deliberate activities in exploring and developing of value creating systems (Ramirez, 1999). According to Normann and Ramirez (1993) the emergence of new value constellations or business opportunities is the result of an

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[45] Path creation highlights the process of mindful deviation, disembedding and unlearning. Due to historical antecedents and the nature of participants, a process evolves which leads to a shared space, i.e. specific knowledge, new patterns of relationships and relevance structures (components of a technological field).

[46] Particularly a network of Danish actors outperformed the US wind energy industry due the development of a viable path of cultivating interactive learning and to harness the inputs of multiple actors to build-up a technological field (labeled as bricolage). The US actors instead believed that the creation of a new industry is manageable through a breakthrough- and technological push approach which in turn leaved not space for interactive learning and the co-creation of a new technological field, i.e. that complementary competences in manufacturing, testing etc. co-evolved.

[47] Studies in the field often draw on a rather simple system understanding, e.g. systems are conceived as markets, business networks with commentary actor networks (Möller, 2010) or as technological system characterized by technical connectedness and prospects from system integration (c.f. Lundgren, 1995) The literature provides useful insights in how networks of actors emerge and how entrepreneurs might proceed in system building (Sarasvathy and Dew, 2005; Möller, 2010).

interplay of a complex set of actors, various economic transactions, and of institutional arrangements among manufacturers, suppliers and customers.[48]

The entrepreneurship literature, finally, not only focuses on ‘who is the entrepreneur’ but is increasingly interested in the entrepreneurial process (Gartner, 1988). Both aspects are important for system-building. First, the literature discusses the features of entrepreneurs in technology entrepreneurship (Shane and Venkataraman, 2000; Shane and Venkataraman, 2003) and concludes that entrepreneurs are individuals who informally emerge in an organization and make a decisive contribution to the innovation by actively and enthusiastically promoting its progress through critical stages (Howell and Higgins, 1990). Second, particularly Sarasvathy and colleagues develop an understanding of entrepreneurial processes in radical innovations (new product / new market combinations) (Sarasvathy, 2001, 2008; Sarasvathy and Dew, 2005; Wiltbank et al., 2006). When faced with ambiguity and high uncertainty, entrepreneurs start from the resources they have at their disposal and continuously extend these resources while they interact with other actors in networks (Sarasvathy, 2001, 2008; Sarasvathy and Dew, 2005; Wiltbank et al., 2006).[49] This strategy -- forging networks of actors and setting up a cycle that increases the resources available -- reduces uncertainty as the new business opportunity is co-created. The creation and coordination of new business opportunities starts if actors pre-commit to a new technological path, persuade others to follow, and set in motion a chain of commitments (Sarasvathy and Dew, 2005).[50] System-building strategies, in other words, have to have a crucial impact on the actor involvement or the embedding processes of distributed actors. Indeed, it is not the exertion of agency but the persuasion of docile actors that is key.

The literature review sheds light on different features of system-building. The literature on LTS departs from a sophisticated system concept and assumes that influential and

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[48] Normann and Ramirez (1993) disagreed with Porters idea of ‘value added’ in linear value networks and proposed that successful companies draw on ‘value constellations’, i.e. firms reconfigure and define roles and relationships among this constellation. Participating firms of a value creating system, therefore, collectively compete against other value constellations (collective competition) (Gomes-Casseres, 2003).

[49] In this literature a specific line of action for problem-solving and decision making which reduce uncertainty and ambiguity as a new business field or market is co-created, is key.

[50] According to Sarasvathy, a pre-commitment is a self-imposed non-negotiable constraints which stacks the deck in favor of or against specific choices (Sarasvathy and Dew, 2003). In radical innovations initial relationships between heterogeneous actors have to evolve in the absence of established routines, trust and clear specifications of future profits. Sarasvathy (2003, 2005) points to the fact that the problem of opportunism and free riding is irrelevant in the absence of visible market opportunities and that the concepts of docility and intelligent altruism (Simon, 1993) explain the emergence of collective action in technology entrepreneurship.

resourceful system builders carefully design a complex socio-technical system. The SCOT literature, in contrast, provides an actor model, in which agency and resources are distributed. Consequently system-building requires the inputs of multiple actors. Through the accumulation of inputs, technology development is not only accelerated but also coordinated (path creation). This coordinating effect is emerging and not a consequence of strategic intervention. In this regard, the SCOT perspective on system-building is quite comparable to that in much of the TIS literature.

The literature on emerging business fields has revealed both seemingly uncoordinated system-building processes as well as those shaped by the strategic intervention of actors. The entrepreneurship literature focuses on the latter model: Through different strategies system builders are able to initiate and steer the co-creation of new business opportunities.

There are two major dimensions for system-building emerging from this brief review. The first is about how the necessary resources and competences are distributed and the second is about how the process of system-building unfolds. Resources required for system-building can be concentrated, e.g. controlled by a single actor, or distributed among a variety of actors. While most of the literature suggests distributed resources and distributed agency, the LTS approach has described situations in which a central actor had the resources and competences to organize system-building. Second, system-building can be coordinated and actively managed in an entrepreneurial way or it can be largely emergent, i.e. without any traceable strategic intervention.[51]

5.2.3 System-building as a resource driven process

In recent studies on emerging technological fields, the coordination of actors in networks and strategic action directed at system-building have increasingly come under the spotlight (Hellsmark and Jacobsson, 2009; Musiolik and Markard, 2011; van der Valk et al., 2010; Weber, 2002). It is described how innovating actors come together in formal and informal networks to create and shape specific support programs, standards, or the legitimacy of a technology, for example. These new system components provide positive externalities for those interested in the novel technology, which is why they have been conceptualized as *system resources* (Musiolik and Markard, 2011). System resources facilitate the creation and diffusion of knowledge, stimulate the entry of new actors, reduce uncertainty, or assign roles to the various actors in an emerging field.

The formation of a technological field, in fact, can be regarded as a constant transformation of resources at different levels (Musiolik et al., 2012). Resources at the

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[51] Note that we use the term 'system building' here for all processes in which system structures are formed or changed non-regarding whether these are rather actively managed or not. In the following, however, we are primarily interested in strategic system building.

organizational level are combined and used to create resources at the system level, which again support the development of new resources at the organizational and so on. Strategic system-building, in other words, is a resource-driven process, in which innovating actors combine, develop and deploy resources at different levels (Musiolik et al., 2012). In the case of radical innovations (new product / new market combinations) system builders might start from the resources they have available and continuously extend these resources while they interact with other organizations in networks and co-create a new technological field (Sarasvathy, 2001, 2008; Sarasvathy and Dew, 2005; Wiltbank et al., 2006). System-building activities are, therefore, determined by both the (organizational) resources system builders have at their disposal but also by the resources they get access to through alliances, networks or systems (Musiolik et al., 2012).

Organizational resources for system-building include technological competences, finances, contacts or the reputation of an organization. These are often complemented by the knowledge, motivations and networking skills of individuals in the organizations. Often system builders have to work in multidisciplinary settings, where reducing ambiguity, finding common ground for collaboration, and inventing organizational and institutional solutions in the face of obstacles, resource constraints, and legacy system remnants is vital (Hajek et al., 2011). Therefore, skills in communication and agenda construction (Möller, 2010), in norm setting, value framing, and other forms of leadership within social processes are important (Hajek et al., 2011).[52]

The resources used for system-building are not static but develop and change over time. Some may even be missing, i.e. they are neither available in the organization in pursuit of system-building nor in the wider network of potential collaborators. Reputation or political influence are examples here (Musiolik et al., 2012). Such resources need to be developed first, which requires time and possibly even specific organizational structures such as networks (Gulati, 1999) or specific associations (Foss and Eriksen, 1995). The set-up of supportive organizational structures can also be challenging and time consuming as governance structures, routines of knowledge exchange or trust between network members need to be established (Musiolik et al., 2012).

Against this background, we can think of different modes, or constellations, of innovation system-building. In the most straightforward constellation, a system builder has all the resources available that are needed to develop a specific system resource. There is no

[52] In the presence of a high level of ambiguity, a lack of legitimacy and recurrent institutionalized pattern of relations and actions (Aldrich and Fiol, 1994; Möller, 2010) system builders are equipped with a transformative capacity (Giddens, 1984), and guided by logic which provides orientation and meaning, and shapes their views of what constitutes legitimate objectives in system building, as well as how these objectives may be achieved (Hajek et al., 2011; Scott, 2008).

need to team up with other actors or to develop intermediate resources, which can then be deployed towards the ultimate goal. In a second constellation, the required resources are distributed across two or more actors and the system builder has to initiate some kind of alliance to also get access to the resources of the others. A third constellation arises if some required resources are not available but need to be created first. In this situation, the system builder has to develop intermediate resources (alone or in an collaboration with other actors), which then can be used for system resource creation.

In the following, we want to explore and compare these modes empirically. We expect that the different modes can be deployed separately or in combination. We also expect that complex tasks of system-building (e.g. the establishment of common standards or the set-up of large-scale R&D programs) require more sophisticated modes of system-building. However, we will not be able to analyze the relationship between task complexity and modes of system-building in much detail.

5.3 Method

The TIS on stationary fuel cells in Germany represents a particularly fruitful case to study the activities innovation system builders. We selected this technological field for three reasons. First, the TIS is still in the formation phase but important technology specific structures (system resources) have already been established in recent years (Musiolik and Markard, 2011). In other words, we could expect several instances of system-building with people who were directly involved still present and active in the field. Secondly, fuel cell technology is not only a radical innovation but also a complex technology, which requires a whole industry to be build up for a well-functioning innovation system.

Thirdly, we could also draw on the data and findings of previous studies (Markard and Truffer, 2008a; Musiolik and Markard, 2011; Ruef and Markard, 2010) which helped us to delineate TIS boundaries (focus on stationary fuel cells and Germany) and to identify key actors and major developments in the field.

The selection of the research site was followed by the identification of system builders and selection of cases in system-building. Our starting point was a review of existing literature on the development of the technological field (e.g. Brown et al., 2007; Nygaard, 2008; Ruef and Markard, 2010) together with the analysis of data from previous studies (Markard and Truffer, 2008a; Musiolik and Markard, 2011; Musiolik et al., 2012). This data could be used to detect key actors as well as 50 formal networks in the field. Moreover, we were able to identify major TIS deficits, in the sense of barriers for further development, system-building activities could be expected to address.

Understanding both the actor basis and major challenges in the TIS was important for the identification of system builders and selection of cases. Moreover, we already knew about some examples for system-building driven by formal networks from our previous analyses (Musiolik and Markard, 2011). In a next step, we therefore came back to some of these networks, analyzed their membership database, selected informants in the advisory boards and other key positions, and conducted interviews with them.[53] In the interviews we discussed major TIS deficits (e.g. missing suppliers, weak value chains) and how they were tackled. We also asked for other actors who had deliberately contributed to TIS deficit reduction (snowball method). At the end of this step we had captured in detail system-building activities in the TIS, and had also identified major system builders in the field. In the following, examples for system-building were selected based on the following criteria: a. there had to be a system builder (a firm, a public organization or an individual); b. the actor initiated innovation activities towards TIS deficit reduction (developed a strategy, deployed resources); c. the activities clearly contributed to the formation of system resources.

With this approach we were able to identify a series of examples for system-building, which we grouped into 7 cases each of which with a clearly identifiable system builder (mostly firms). On these cases we followed up with further in-depth interviews and studies.

For the preparation of each interview, we examined company websites, annual reports, newsletters, firm homepages and newspapers articles. Semi-structured expert interviews were then conducted. Every interview included questions about the (external) innovation activities of the organization, its involvement in formal networks, the reason for the initiatives and the perceived benefits of conducting activities directed at the system level. 16 interviews were carried out with key system builders (1.5 hours on average), and another 32 interviews (same empirical fields but other informants) could be used as additional sources of information (triangulation).

Interviews were fully transcribed and consolidated with the other documents in a database. In the subsequent text analysis we assigned labels to text units. We began by identifying the activities which system builders had directed to system resources generation and also identified the organizational and network resources they had used to solve the specific TIS deficits. Activities which resulted in exclusive benefits for the organization (e.g. development of patents) were not part of the analysis. In a final step, the findings were arranged following a comparative multiple case study design (Eisenhardt, 1989; Yin, 2009).

5.4 Observed system level activities and modes of TIS-build-up

In this section we present the 7 cases of system-building and identify typical modes of system-building.

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[53] Formal networks have a clear identifiable set of member and governance structures, such as advisory boards or working groups (Musiolik and Markard, 2011). For tracing key members in the networks we used the information available at the websites of the networks.

5.4.1 Observed system-building cases

In our analysis we identified 7 different cases which were crucial for the build-up of the technological innovation system on stationary fuel cells. In Table 11 these cases are depicted. The table starts with a case label which points to the focal system builders. This is followed by, a list of detailed activities towards system build-up and finally achievements, i.e. the system resources which have been created and shaped through this initiative. Below we will discuss the different cases according to the identified TIS deficits which had to be solved (cf. section 5.3).

Weak knowledge base

The creation and diffusion of basic scientific knowledge is key for TIS formation and the value appropriation by private firms (Van de Ven, 1993). In the ZIP R&D program case, public authorities played a key role in strengthening the knowledge base in the area of fuel cells in Germany. Triggered by the energy crisis and environmental concerns, state actors started to support basic research of hydrogen and fuel cell technologies in Germany.[54] Public authorities developed strategies to better support the development of hydrogen and fuel cell technologies and launched in 2000 a special program for residential fuel cell heating devices, and the ‘Zukunfts-Investitions-Programm’ (ZIP), from which more than half of the funds for fuel cells (about 60 Mio. Euro for three years), were allocated to stationary applications. As a result, a specific support program was created and the basic scientific fuel cell knowledge increased. The program triggered additional investment from universities and industry partners. Through newly established R&D consortia, not only were core partnerships and value networks initiated but also important artifacts such as specific fuel cell components created and made available in the field. The step from basic research to applied R&D and field-tests was finally accompanied by the foundation of fuel cell specific research institutes.

Suppliers missing

In the TIS for stationary fuel cells, core components were costly and produced in low quality and low numbers. Established suppliers for such components in other industries had valuable manufacturing capabilities but little understanding of specific requirements of the fuel cell technology. Qualification and integration of component suppliers was therefore necessity. Two fuel cell manufacturers (CFCL and Baxi-innotech) addressed this deficit.

In the CFCL case, a leading manufacturer managed its supply chain in pro-active way. CFCL acquired specific technological knowledge to produce and optimize a highly efficient fuel cell. However, on the step from small scale to mass production the firm realized that

[54] Later on, this energy political motivated support was supplemented by local business development initiatives in the federal ‘Bundesländer’.

central ceramic components were needed at a lower price and in a better quality. The company, therefore, developed a strategy to employ the manufacturing capabilities of established suppliers. CFCL chose partners from the German ceramic industry, non-exclusive collaboration agreements were established and specifications, technological knowledge and licenses deliberately transferred to the suppliers. While CFCL was supervising the development of the ceramic components, the suppliers could sell the components also to other manufacturers. Based on the higher demand it was expected that the component price would decrease while its quality would be continuously increase on the way to mass production. In sum a deliberate knowledge transfer and strategic cooperation, therefore, lead to the qualification and integration of suppliers, new parts of emergent value network and the co-creation of cheap ‘standard’ components.

Baxi Innotech was following a different strategy towards supplier qualification and integration. It was reported that Baxi was a leading actor in the VDMA fuel cell working group and thus shaped the strategic direction of joint activities in the working group. The company motivated partner suppliers to enter the network, communicated its technological specification, and thus contributed to the generation of joint understanding of fuel cell requirements among the network members. In addition to that, Baxi and other VDMA members established an additional institutional structure: the KGP support program. This program was created to finance and supervise small scale R&D projects, e.g. the adjustment of standard fuel cell components (e.g. pumps, valves). By exchanging requirements between system manufacturers and suppliers in the network, and the subsequent execution of R&D projects an orchestrated adaption of fuel cell systems and components was initiated. Due to these activities Baxi trained and integrated suppliers, contributed to the establishment of an efficient network of technology developers and influence the adaption of ‘standard’ components. Interestingly, Baxi also used the network to introduce preliminary standards (e.g. a Japanese connector technique) and to initiate the subsequent adaption of components and fuel cells.

Market immature

The successful market launch of stationary fuel cells depends highly on the interests of end costumers, and the definition of the actor roles of energy service provider, fitters and other downstream service providers in an emergent value chain (Musiolik, 2011). It was reported that the field-testing activities were highly interrelated to other subsequent market preparation activities. Energy service provider such as EWE were developing and legitimizing their business models and active in regional field testing (EWE case.) as well as in formal networks (EWE IBZ case) to promote market preparation and formation at a national level.

EWE as a leading energy service provider in the field installed and tested several hundred fuel cell pilot plans since 1998. Through the field tests EWE provided finance, pilot costumers and distribution channels to manufacturers in Germany. A business platform between EWE and a local association of fitters was also founded. Through this cooperation, EWE introduced contracting models onto a regional market. It was reported that the involved actor groups, i.e. EWE, fitters and end customer, accumulated experience with contracting and the handling of stationary fuel cells, thus routinizing their interaction as service process became established. EWE steered and initiated the whole process. The qualification, integration and preparation of local fitters went hand in hand with other complementary activities: EWE also founded an information center and conducted information campaigns to present smart energy and building technologies. As a result, both fitters and a wider public were prepared, and the interests of future customers were raised. In this way a nursing market (Ericsson, 1989) was provided to support and stabilize fuel cell manufacturers.

In the EWE IBZ case, EWE established and steered the IBZ fuel cell initiative and the associated Callux project network. Due to the complexity of the fuel cell technology EWE realized that local initiatives are not sufficient to introduce stationary fuel cells onto the market. Therefore, the energy service provider initiated joint activities in market preparation and formation. Crucial was here the IBZ fuel cell initiative which was established in order to prevent technological hype and further miscommunications (Musiolik and Markard, 2011). EWE has a key role in this network. Due to joint activities, trust and an efficient network structure emerged. EWE used this organizational (network) structure to accelerate the market introduction and to initiate a joint field test and joint market measures (in the Callux project network). Here, network members jointly worked on technical solutions, on regulations, codes and standards (e.g. the standardization of interfaces) as well as development of a module for vocational training of down-stream services providers. As a result, supportive framework conditions such as expectations and awareness of stationary fuel cells were influenced in positive way. Activities in Callux and in the IBZ fuel cell initiative lead to establishment of standards, and the qualification and integration of downstream service providers through a program for vocational training. Finally, through Callux and the joint installation of several hundreds of fuel cells also a bridging market (Andersson and Jacobsson, 2000) was provided.

Weak governance of TIS development

In many cases, the formation of new TIS lasts for years and may evolve in a rather uncoordinated way (Jacobsson and Bergek, 2004). A strategy for structuring and coordinating the formation of a TIS, i.e. exerting governance and realizing synergies, however, becomes quite important if different TIS compete. Compared to the innovation activities in Japan and USA, the development of the fuel cell field in Germany was uncoordinated. As central actors were afraid of losing ground, a massive bundled and coordinated initiative in Germany was realized: EWE and other system builders lobbied and organized a National Innovation Program (NIP) Hydrogen and Fuel Cell Technology (Fuel Cell Alliance case). Later on, the NOW program organization was also founded to coordinate and structure the implementation of the NIP program (NOW case).

In the Fuel Cell Alliance case, key system builders from the fields of stationary, mobile and portable applications took the initiative to write a fuel cell strategy paper, to organize meetings with politicians and thus coordinated and activated an advocacy coalition

(Sabatier and Jenkins-Smith, 1993) in the Fuel Cell Alliance Germany. Separate or loosely coupled working groups and actors were organized in new overarching networks while the federal ministries also bundled their fuel cell activities. As a result, all relevant system builders of the field worked together closely in a strategy group. An unstructured discussion of aims was structured and lead to the establishment of a joint fuel cell roadmap (the National Development Plan). After the federal election in 2005, the strategy group identified a window of opportunity to link up with the new government and to submit the idea of a national fuel cell support program. The NIP support program became anchored in the new government's coalition agreement, a public-private partnership between industry, science and federal government was realized, and a program organization (NOW GmbH) was created to implement the NIP. Meanwhile the NOW advisory board, a new network, was established to represent the fuel cell system builders and networks. As a consequence, not only were these new system structures established, but the fuel cell community was also organized and could operate on the interlinked overarching networks (e.g. VDMA, IBZ, NOW advisory board). Interestingly, the key system builders of the formal networks of the field also played a key role in the newly created NOW advisory board and could further influence the progress of the field.

The NOW case showed that the coordination of an emerging field is still an issue even as a NIP support program is created. In order to avoid competitive issues and to steer the direction and speed of the NIP support program, the NOW organization was created. The intermediary organization coupled projects to lighthouses (i.e. bigger project consortia such as Callux) and thus supervised the selection of firms according to the needs of the value chain, i.e. NOW managed R&D and supply chains. In addition to that, the organization tried to solve emerging problems, in the interplay of basic research, applied R&D and field testing through mediation of different interests. For instance, NOW facilitated the communication between industry and ministries, and initiated the modification of regulations and funding schemes. The program organization also promoted cross-sectional tasks and conducted information campaigns about NIP projects and the fuel cell technology, while also supporting the international exchange and the presence of the German industry in international standardization boards. The NOW activities had various effects: Firstly, synergies between projects and strong networks of actors within the different applications could be identified and realized. Secondly, NOW could increase the (international) awareness and assertiveness of German fuel cell sector.

Table 11: Cases in which system builders contributed to structural build-up

	a. **ZIP case**	b. **CFCL case**	c. **Baxi-VDMA case**	d. **EWE case**	e. **EWE-IBZ case**	f. **Fuel Cell Alliance case**	g. **NOW case**
TIS deficit	Weak knowledge base	Supplier missing	Supplier missing	Market immature	Market immature	Weak governance	Weak governance
Focal system builder	Federal ministries	CFCL manufacturer	Baxi Innotech manufacturer	EWE energy service provider	EWE energy service provider	VDMA working group, IBZ network, ZSW, Fuel cell Europe	Manager of NPW intermediary organization
Activities towards deficit solutions	Developed strategy to support basic research due to energy crises, environmental concerns allocated 60 million of funding between 2000-2003 shifted towards applied R&D, field tests in ZIP program due to industry and business development concerns founded fuel cell research infrastructure in federal states (ZSW and ZBT institutes)	identified the need of manufacturing capabilities of suppliers strategically chose suppliers for none exclusive collaboration contracts transferred knowledge, specification, licenses, means of production to supplier supervised and supported the production of cheaper ceramic components with higher quality (1st step towards for mass market)	CEO became head of steering committee of the VDMA working group, shaped the strategic direction of activities motivated suppliers to become members exchanged its fuel cells specifications, contributed to generation of joint understanding of fuel cell requirements influenced creation of KGP specific support program, supervised projects in KGP program introduced and diffused Japanese connection technique	started field testing, provided finance, costumers, distribution channels, contacts to local fitters founded a cooperation with local fitters, introduced contracting models, trained local fitters, architects, planning offices in installation, maintenance of fuel cell heating systems founded information and training center "zentrum zukunft" conducted info campaigns	stabilized manufacturers after fuel cell hype promoted establishment of joint lighthouse project Callux initiated joint market measures, guidelines for fitters work on joint technical solutions for technical and legally obstacles, worked on regulations, codes and standards, initiated and developed smart grid solutions	met to activate and organize the field in 2005 wrote a strategy paper, founded the Fuel Cell Alliance Germany convinced relevant federal ministries to bundle activities, founded a strategy group crafted draft of a fuel cell road map (NEP), developed NIP program structure, idea of NOW project organization used NEP and window of opportunity after elections in 2005 to anchored NIP program in the new coalition agreement	supervised selection of NIP projects, coupled projects to lighthouses, manage R&D and supply chains mediated interests between different parties, the adaptation of NEP, initiated the modification of regulations, funding guidelines promoted cross-sectional tasks: joint work in international standardization committees, fuel cell campaigns, and international exchange etc
Created / shaped system resources	R&D support program Strengthened scientific knowledge base initial partnerships and value networks technological artifacts, integrated fuel cell components ZSW and ZBT as new actors with crucial competences	direct qualified, integrated supplier as new actors with crucial competences technological artifacts, specific standard components for stationary fuel cells new part of value chain	qualified, integrated supplier as new actors with crucial competences establishment of an efficient network of technology developers technological artifacts standard components, standard connection technique KGP support program	trained service providers, established service processes (regional) awareness and image of stationary fuel cells raised interest of end costumers local nursing market	formal network of key stationary actors bridging market , increased awareness of stationary fuel cells technological artifacts, desulfurization cartridge vocational training program, trained service providers, established service processes	organized fuel cell community, new network structure (NOW advisory board) NEP a joint national fuel cell roadmap, NIP a public private partnership between industry, science and federal government and NOW as program organization of NIP	governance structure to manage field development, avoid competitive issues and to created synergies and guidance strong networks of actors in the branches of different applications (e.g. Callux) caretaker, coordinated position in international standardization boards

This became for instance visible through the employment of a joint caretaker and a coordinated German position in international standardization boards. Thirdly, a governance structure to manage systemic field development was established, while competitive issues have been avoided and synergies and guidance have been created.

The comparison of the different cases shows that system builders initiate activities to solve common TIS deficits and to fulfill system-building tasks. It seems that these challenges, or TIS deficits, are typical for new technologies. However, what is more important here is that different system builders had chosen different strategies to solve these common problems. The general pattern which emerges from the description is that in some examples a single organization or pair of actors, and in other cases a network of actors was involved in initiating and executing system-building. In the next section we elaborate on these findings and delineate different system-building modes.

5.4.2 Typical modes of system-building

In this section we delineate the strategies or modes of system-building typically used by innovating actors. We use the term 'mode' to label a specific constellation and pattern of activities for TIS build-up. Different modes of system-building may be applied due to the presence of specific system builders, the distribution or creation of the resources needed, and the complexity of the system-building task.

In the CFCL- and EWE cases, specific organizations had a vision about their future role in the field and developed a strategy to integrate the resources needed and to involve other complementary actors. Accordingly, they transferred their organizational resources such as technological knowledge, patents or finance to selected partners in order to initiate additional activities and to indirectly create system resources such as key fuel cell components or nursing markets. Finally, the established partnerships and the created system resources additionally increased the actor involvement. [55]

In the Baxi-VDMA and EWE-IBZ cases a network of actors had to be coordinated to initiate and execute system-building. Here, the development and deployment of collective resources and the (direct) creation of system resources were in focus. Baxi and EWE, as system builders, were steering these processes not only to create complex system resources such as standards, or bridging markets, but also to involve and train complementary actors such as suppliers and fitters through the networks and the created system resources (e.g through created vocational training programs).

[55] While the partner actors trained and qualified they also invest in the development of own resources and capabilities and become further committed into the field. New resources enable the partner to transform his own business activities and produce components or provide services for other actors in the emerging technological field.

In the Fuel Cell Alliance case, the activation of an advocacy coalition of key system builders, rather than the training of complementary actors, was in focus. Here system builders depended on the resources of public authorities to create and shape complex system resources. Therefore, the strategy was to initiate the indirect creation of system resources through the lobbying of public authorities. The created and shaped NIP support program is a key system resource for further TIS development and actor involvement.

Finally, the ZIP R&D program case and the NOW case are rather specific. Here, focal system builders could draw on resources they already had at their disposal, and could directly shape or create system resources without the help of other actors or networks: public authorities thus provided the ZIP support program to initiate the development of basic scientific knowledge, while the NOW organization was put into place to manage the implementation of the NIP support program and to provide system-building services to the emergent field. Also here, further actor commitment was initiated by the creation and shaping of system resources, i.e.ZIP and NIP support program.

Typical modes of system-building can be delineated according to the aforementioned constellations and patterns.

Table 12 summarizes typical modes and depicts their different features.

The ZIP R&D program case can be labelled as '*prime mover mode'*: a single resourceful and powerful actor identifies a key technology, provides its organizational resources to create system resources, and activates and steers the activities of, for example, science and industry.

In the CFCL- and EWE cases, the resources needed for system-building were distributed and system builders deployed their organizational resources to integrate and qualify strategically chosen partners, while system resources such as a nursing market, or new parts of a value chain, have been co-created. That is why we label this system-building strategy as the '*alliance mode'*.

As system builders and many other actors collaborate in formal networks in order to directly establish system resources such as standards, we differentiate between the '*alliance mode'* and an '*orchestrated mode'*. An orchestrated strategy co-evolved with the resources networks had at their disposal.[56] The system build-up activities in the BAXI-VDMA and EWE-IBZ cases clearly showed that the orchestrated mode is about organizing and steering collective action: system builders moderate and influence joint activities to directly co-create network and system resources.

[56] To give an example, firstly suppliers became qualified through the communication in the VDMA working group of fuel cells. Secondly, the network could also draw on the created KGP support program. In fact both activities were coordinated, and the knowledge which was generated in the network was used for executing R&D projects in the support program.

Table 12: Typical modes of system-building

Descriptions of the modes

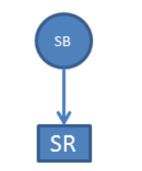
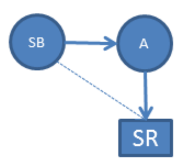
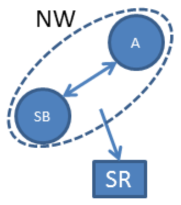
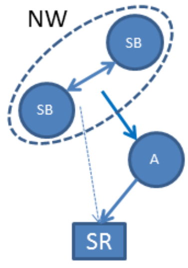
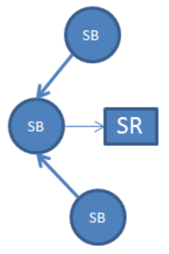
Mode 1 (prime mover mode): A resourceful and powerful actor directly creates a system resource to stimulate the development of a new technology. The system resource build-up is not particularly demanding or overly complex. Example: state actor(s) set up a R&D program for a specific technology.

Mode 2 (alliance mode): An actor who cannot create a system resource on its own involves one or more other actors with important resources in the system-building process. The system resource build-up is not particularly demanding or complex. Example: Technology developer qualifies a supplier for a specific, non-exclusive product development task.

Mode 3 (orchestrated mode): Two or more resourceful actors form a network. While a key actor initiates and steers joint activities, the network directly creates a system resource. The system resource build-up is demanding. Example: Common development of industry standard(s).

Mode 4 (coalition mode): Two or more actors collaborate closely to convince a third party to mobilize resources for system-building. The system resource build-up is demanding. Example: Industry lobby convinces policy makers to set up a (market) support program.

Mode 5 (intermediary mode): Key actors initiate the creation of an intermediary organization to take care of specific tasks within the TIS (i.e. to manage system resources). Example: key actors launch a specific association which provides particular services for emergent industry.

Mode	1. Prime mover mode	2. Alliance mode	3. Orchestrated mode	4. Coalition mode	5. Intermediary mode
SB=System builder A=Actors SR=System resource NW=Network → Direct influence ⇢ Indirect influence					
Cases	ZIP case	CFCL case, EWE case	Baxi-VMA case, EWE-BZ case	Fuel cell alliance case	NOW case
Typical players	Public authorities, foundations, multinationals	Manufacturers, key users	Manufacturers, key users, champions	Manufacturers, key users, champions	Industry associations, other intermediaries
Strategy of SB	Top-down creation of SR	Transfer of organizational resources, for (indirect) creation of SR	Development, deployment of collective resources for direct creation of SR	Activation of advocacy coalition, deployment of collective resources for (indirect) creation of SR	Deployment of intermediary for system building services
Actor involvement / commitment	Involvement through SR	Involvement through alliance and SR	Involvement through network and SR	Involvement through advocacy collation and SR	Involvement through SR

Source: own depiction

In the Fuel Cell Alliance case, however, the situation is different as the establishment of a coalition of system builders is needed to indirectly create system resources such as a support program. Here a network of system builders initiates lobbying activities to incorporate a resourceful actor such as the state. That is why we call this pattern of activities the ‘coalition mode’.

Finally, the NOW case is also specific. An intermediary organization is created by system builders of the field to manage the implementation of a key system resource. This intermediary organization draws on the transferred power and reputation while influencing the development of the technological field as such. Therefore we label this the ‘intermediary mode’.

5.5 Comparison of typical modes

Each mode depends on different types of resources and competences and therefore might be appropriate for different constellations and situations in the TIS build-up. In the next section, we compare the modes according to the types of resources system builders have to have at their disposal, before discussing features of deliberate system-building in a more general way.

5.5.1 Resources dependencies of the modes

The resources and system-building skills needed differ between the five modes. Again, resources-driven system-building depends not only on certain organizational resources or system-building skills but also on collective resources system builders can draw on. Table 13 depicts the dependencies of typical modes on specific types of resources.

The *prime mover mode* depends highly on organizational resources such as finance, while the need for system-building skills is rather low. For an effective alignment of policy, science and industry, and the development of an essential knowledge base, both financial resources and some skills in designing an effective system resource (e.g. R&D program) might be crucial. System-building skills, coordination and the use of collective resources are less important while (organizational) resource endowment is key.

This also holds true for the *alliance mode*, in which system builders just have to identify and involve valuable partners and to use both their organizational resources and the partner’s resources for system resource creation. However, for the persuasion of partner firms and the formation of alliances, collective resources such as the image of the technology or positive collective expectations are often additionally important.

Table 13: Typical modes and their dependencies on different types of resources

Mode	1 Prime mover mode	2 Alliance mode	3 orchestrated mode	4 Coalition mode	5 Intermediary mode
Organizational Resources	++	++	+	++	++
SB skills	O	O	++	++	++
Collective resources	O	+	++	++	O

++ high, + medium, o low

Source: own depiction

In the *orchestrated and coalition modes*, collective resources and significant system builder skills are key. Organizational resources such the power and reputation of an organization increase system-building abilities, while system-building skills are particularly important: experts who become active in formal networks or in advocacy coalitions must have skills in reducing ambiguity and finding common ground, and finally have to form a network capable of working to create and shape complex system resources. Without key system builders, who also strategically initiate and guide collective activities, alignment of actors in the field would be difficult. In fact, in addition to system builder skills, the establishment and deployment of collective resources such as governance structures, trust between the members, or network reputation are important for both modes. In comparison organizational resources might be more important in the coalition mode as abilities in lobbying are affected by the power and reputation the organizations contribute in the advocacy coalition.

Finally, the *intermediary mode* draws strongly on organizational resources such as reputation and power which are assigned to the intermediary organization. In addition to that, skills in system-building are needed to identify TIS deficits, steer system resources development and to mediate the interests of different actor groups in the TIS build-up.

Every mode depends on the access to specific resources or system-building skills, and each one might be appropriate for specific actor constellations or TIS phases. For some modes the development and access to collective resources is crucial and therefore their deployment by system builders might depend on certain preconditions. For instance, without the provision of basic scientific knowledge through R&D programs, industry firms would not move on in the alliance mode to create further system resources. And, as previously mentioned, innovating actors cannot simply start with the orchestrated mode. The actors in a technology field have to become coordinated, and to assign legitimation and a specific role to a selected network, before the mode is applicable for collective actions and specific TIS building. The same holds true for the intermediary mode. In an emerging field actors have to become coordinated before they can assign a specific role to an intermediary organization, which then provides services in system-building.

System builders can be expected to constantly enlarge the modes for system creation. The availability of different modes increases their strategic options to steer and accelerate TIS development. However, in the later phase of TIS formation, all modes were constantly used to build up a TIS. System builders such as manufacturers frequently trained their direct suppliers and influenced the availability of components through their alliances, while at the same time pushing standardization and supplier qualification through the established formal networks. Interestingly, in our empirical study key system builders took the initiative, and do not only contribute to TIS build-up, but also occupy key positions in the newly created governance structure (for collective actions).[57]

5.5.2 Key features of strategic system-building

In this study we did not focus on cumulative causation, critical mass and other emergent system-building processes. Instead we focused on strategies of system builders and delineated modes which they typical use to initiate and coordinate TIS build-up. These modes provided some insight into the nature of the system-building process. Deliberate system-building involves four key features: a. the presence of system builders, actors who gets things started; b. the coordination and initiation of collective action to create and shape system resources; c. the provision of positive externalities (system resources) to initiate, activate and facilitate the innovation activities of complementary actors; d. multiple-goal strategies, i.e. innovation activities to bring and (keep) multiple system components into a coherent whole.

System builders, pivotal resourceful organizations or individuals that bring significant resources and/or competences in leadership and agenda setting to the table, have been key in all cases of deliberate system-building. In some cases the initiation and execution of deliberate building strategies rather depended on the organization, and in others merely on specific people, so-called champions. Some organizations execute and initiate system-building continuously (independently from specific individuals), as the creation of a specific business field is part of their overall firm strategy (Musiolik, 2011; Ramirez, 1999). In the case of champions, system-building activities might reflect their personal enthusiasm and passion for the technology (Howell and Higgins, 1990). Both types of system builders develop and realize strategies to develop and steer the development of TIS.

The coordination and initiation of collective action is another crucial element. System builders depend on the commitment of other actors as the resources for technology entrepreneurship are distributed and single actors can hardly create and shape a new technological field alone (Garud and Karnoe, 2003). However, steering the involvement of multiple actors is not only important in terms of a division of labor and reducing uncertainty but also in terms of increasing the legitimacy of a new technology (Aldrich and Fiol, 1994). System-building strategies, in other words, have to have a crucial impact on actor involvement or the embedding processes of distributed actors (Sarasvathy and Dew, 2003; Sarasvathy and Dew, 2005). A critical determinant for deliberate system-building is therefore how actors are organized in, for example, formal networks, in addition to how

[57] In the case at hand, system builders did not only develop and deploy different modes, but also moved from one key position to newly established key position: key members of the formal networks (e.g. VDMA and IBZ) became also the decision makers in newly established networks or governance structures such as the NOW organization or the NOW advisory board.

docile the actors in a specific field are. Technological initiatives which do not build upon the input of many actors may neither mobilize the required skills and resources nor ensure acceptance in the wider community (Garud and Karnoe, 2003; Garud and Karnøe, 2001).

The provision of positive externalities characterizes deliberate system-building. In contrast to established product markets, in which firms are trying to prevent, for example, knowledge spill-overs and free utilities, positive externalities are deliberately created to initiate and facilitate the innovation activities of complementary actors. Again, technology entrepreneurship depends on the commitments of many different actors. All cases showed that deliberate system-building activities go beyond conventional technology and innovation management. System-building resulted in the creation of system resources which provide positive externalities beyond the immediate benefits of single actors (Musiolik and Markard, 2011). Created and shaped system resources facilitate and initiate the 'entry' of further actors and reduce the overall uncertainty and ambiguity.

Multiple-goal innovation activities, finally, have also been crucial in all cases. Following the ideas of Callon (1987), system-building is about intentional activities to bring different system components into a coherent whole, and to keep them that way.[58] With deliberate system-building, it was often the case that not only the creation of certain system resources was key but also secondary goals such as positive influences on collective expectations, the legitimation of the technology or the entry of further actors next to reduction of the overall uncertainty and ambiguity. To give an example, system builders had set up a national support program in Germany not only to increase the financial resources and to structure and organize the emergent field of fuel cells in Germany, but also to increase public awareness of the technology (Musiolik and Markard, 2011).

5.6 Conclusions

5.6.1 Contribution to the TIS literature

This chapter and its focus on strategic system-building complements the innovation systems literature in several regards. First, it sheds light on the role of the actor group of system builders in TIS formation. The innovation activities of distributed actors add up to more than just certain TIS functionality (cf. section 5.2.1). Our study of the TIS of stationary fuel cells has clearly shown that system builders might play a key role in the coordination of the TIS build-up and that they realize 'hidden' opportunities of new technologies by creating and shaping supportive structures: they identify TIS weaknesses, assign roles, and steer and initiate the activities of complementary actors, which often

[58] Components make up a system because they interact functionally to fulfill a system goal (Carlsson et al., 2002b; Hughes, 1986). They permanently interact and changes in one component lead to influences at another side of the system or will trigger a set of actions and reactions.

leads to the establishment of system resources. As a consequence, system builders can have a crucial impact on the structure of an innovation system, i.e. how complementary system components are brought into a coherent whole. System builders might also be able to manipulate distinct paths of technology development, i.e. favoring specific socio-technical variants of the innovation while excluding others (Markard et al., 2009). Identifying system builders and analyzing their strategies and resources, therefore, can therefore be essential not only to analyze TIS performance developments but also the creation of technological paths.

Second, we achieved a better understanding of the interplay of system builders and others actors in technology innovation. Our study has shown that a more distinct differentiation of different types of networks is key to uncovering ‘channels’ for deliberate system-building. In this study, system-building was coordinated either through alliances, i.e. the initial ties manufacturers developed with their suppliers and customers, or through working groups of associations and other types of formalized networks of actors in the field. It seems that the type of network determines the output of the initiatives. In (informal) alliances, system builders transferred knowledge and other organizational resources to create and shape initial business networks or nursing markets, while in formal networks more complex system resources (e.g. standards, support programs) could be created. In addition to that, the role of system builders in steering and leading formal networks has to be taken into account. Different system-building capacities of formal networks can be traced back to both heterogeneous resource portfolios of networks (Musiolik et al., 2012) and the very presence of capable system builders. Formal networks represent not only a shared space for the interactive emergence of new technological fields (Garud and Karnøe, 2001), but also organizational structures for initiating and steering collective action of docile actors. Moreover, system builders can use formal networks to strategically develop collective resources such as trust or reputation and power to stabilize actors in the process of innovation, and even to increase their abilities in system-building.

Third, the chapter also contributes to a better understanding of the process of TIS formation. The modes identified might evolve over time from the least complex prime mover mode to the more demanding orchestrated or intermediary modes. Again, it might take time until crucial actors are organized, collective resources are established and a formal network or an advocacy coalition becomes capable of work. In addition we observed the professionalization of the organizational structure (networks) which system builders can draw on to initiate, steer and accelerate system-building. It seems that the system-building process went through a start-up period with a transition from external to internal sources of change, and took off, i.e. could grow on its own, as formal networks and even specific intermediary organizations were created to conduct TIS build-up (c.f. Van de Ven and Garud, 1989).

Consequently, system-building is not only about successively emerging structures in a new field (Garud and Karnoe, 2003; Garud and Karnøe, 2001), but also about deliberate planning, or what Lundgren (Lundgren, 1993) has labeled the ‘great design’ of new technological fields. Our results showed that in certain TIS phases the achieved modes were insufficient to develop the technological field any further. At this stage, system builders were able to bring the emerging path to higher levels of coordination and development. Furthermore, the planning and execution of activities was separated. System builders can then accelerate or leapfrog certain development paths, as they are able to put the activities on a higher level of coordination: they create and shape system resources such as national support programs, which in turn lead to new governance structures or new modes of system-building.[59] Therefore, in many cases, neither 'breakthrough' nor 'bricolage' (Garud and Karnoe, 2003) will exclusively explain certain paths, but often a mixture of both approaches might better account for the emergence of new technological fields (cf. Hendry and Harborne, 2011).

5.6.2 Contribution to policy making

Policy making is currently focused on system failures. According to functional analyses, policy makers should react to what is currently happening in the system, and care about blocking and enhancing mechanisms which influence subsequent system functionality and performance (Bergek et al., 2008a). As a result of this focus, we might lose sight of the fact that TIS are also created and shaped, and that central system builders can be at work, which might need support but also might be observed carefully for not excluding technological options prematurely. We argue that the chances of success in a new field depend highly upon the ability of system builders to shape and create supportive socio-technical systems. A critical moment of TIS evolution is the formative phase, which is why TIS studies should not only inform policy makers about the current functionality but also about the system-building processes.

In general, an analysis of the available modes of system-building improves understanding of what system builders can actually do, and when public authorities have to step in. In Germany, at a certain point system-building skills and the reduction of ambiguity, rather than financial support, were important for the development of the field. Within the ZIP support program many R&D resources were made available, which led to different but rather uncoordinated activities. While starting with fuel cell activities, firms realized the complexity of the technology and learned that standardization and interaction with other manufacturer and supplier were crucial. However, it took several years until an efficient

[59] In early TIS, entrepreneurs were not able to draw on any supportive infrastructure at all. They had to start from their established organizational resources and partnerships, and continuously extend the resources and modes they could draw on to shape the environment they were operating in. Only after networks and supportive structures were created, which guided, stabilized and legitimized the new field, could entrepreneurs move towards a more design-based approach and finally to the intermediary mode to outsource system building to intermediary organizations.

industry network in Germany was established. The same holds true for the development of the joint roadmap (NEP) and the NIP support program. Also here, it took more than 10 years and much effort from key system builders. Therefore, not only support in establishing new system-building modes, but also the specific support of capable system builders, who search for common ground and span boundaries, is critical. This is related to a better combination of policies which target the establishment of new markets, or stimulate entrepreneurship. Future studies at the intersection of the entrepreneurship, strategy and innovation system literature can be expected to make important contributions to these challenges.

6 Conclusions and outlook

This final chapter summarizes our main findings and gives answers to the research questions. We then discuss the contribution of this thesis to the literature, and identify further research needs.

6.1 Summary and answers to the research questions

RQ 2a: Why do actors differ in their importance for TIS? RQ 2b: Why do actors deliberately contribute to creating and shaping system resources?

In chapter 2 we conceptually developed key features of ‘resource based reasoning’ in TIS. Our starting point was that innovation activities and strategies of firms and other organizations depend on the resources they have at their disposal. Given our interest in the strategic build-up of technological innovation system, we suggest distinguishing organizational resources, network resources and system resources. This distinction is based on two key dimensions: where and how they were produced, and who can exert control and/or capture their benefits. On the basis of this differentiation of resources, we developed a framework for innovation system-building, which explains the development and change of institutional structures at the system level (system resources) as a continuous transformation of organizational, network resources, and system resources, which is driven by the strategic activities of specific actors, so-called system builders (cf. chapter 5).

Actors differ in their importance according to the organizational resources they own or control. Some actors might have access to very specific resources, which are crucial for system-building. The EWE energy service provider is a good example here (cf. chapter 5). In addition, the value of an actor’s portfolio of resources might depend on resource complementarities, i.e. the establishment of complementary resources at the network or system level. TIS development in terms of system resource creation can decrease or increase the value of the organizational resources which innovating firms have at their disposal. The framework thus improves understanding of the interplay of strategic moves of key actors and the creation of network and system resources: system builders may benefit from complementarities which derive from the co-creation of organizational and collective TIS resources.[60]

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[60] First mover advantages might also explain the creation of collective TIS resources against the possibility of freeriding. System builders can spur the development of a field or may have a better understanding (absorptive capacity (Cohen and Levinthal, 1990), informational advantages) of how a new technological field will evolve, and which organizational resources might become valuable. Furthermore, the control of uncertainty and ambiguity, and the risk of

RQ 3a: What kinds of supportive structures or system elements do formal networks shape or create? RQ 3b: How do these elements contribute to the functioning of the innovation system, and what kinds of benefits do they generate for innovating firms?

Chapter 3 revealed that the strategic moves of firms and other actors had a substantial impact on the development of a supportive TIS in the field of stationary fuel cells. Actors came together in formal networks to create and shape system components such as support programs, vocational training modules, common standards, new intermediary organizations or technology specific artifacts. These structural TIS components are of strategic relevance and increase the opportunities of innovating firms in the field: they positively influence TIS functions and provide benefits, e.g. by contributing to the assignment of roles to complementary actors (value chain creation) and reducing uncertainty and ambiguity.

RQ 4: Why do networks differ in their ability to influence system resources and which kinds of formal networks might be important for the build-up process of an emerging TIS?

Chapter 4 empirically revealed the importance of the interplay of different resources at different levels in TIS. The abilities of networks in system-building are based on the organizational resources contributed by network members, as well as the network resources which are (strategically) established through the interplay of actors or accumulated within the formal network. In addition to that also changes at the system level, i.e. the creation of system resources also had an impact on the strategic value of resources portfolios of networks. For example the power and reputation of the IBZ fuel cell initiative was positively influenced by the establishment of the NIP support program the NOW advisory board (c.f. chapter 4).

It was revealed for instance that resources of networks such as reputation and power are crucial in the competition of different technologies and networks in innovation. Again, resources have different characteristics, and the actual resource portfolio networks have at their disposal determines which tasks the network can pursue at the system level. Networks, which primarily draw on network resources (reputation, power, common understanding of strategic goals, etc.), are often technology-specific and might be crucial for system-building, especially if different applications compete for public support or public attention.

RQ 5 How do innovating actors proceed in system-building and which typical modes do they use?

In chapter 5 our framework of resources at different levels was used to delineate the system-building strategies actors have available. While analyzing the activities of key system builders five different strategies or modes were identified. In the *prime mover*

being excluded from reaping the benefits of collective resources, drive this engagement in system building (Lieberman and Montgomery, 1988; Sarasvathy and Dew, 2005).

mode a resource- and powerful system builder relies primarily on its organizational resources to directly create a system resource and to stimulate the development of a new field. In the *alliance mode*, a key actor deploys its organizational resources but involves a partner to co-create a system resource. In the *orchestrated mode* a system builder steers joint activities and the development and usage of resources in networks. System resources are, here, directly created or shaped by the network. In the *coalition mode* key system builders cooperate and establish an advocacy coalition. Here system builders complement their organizational resources (power, reputation) and jointly deploy them to persuade a resource- and powerful actor, which then creates a system resource. In the *intermediary mode*, finally, key system builders initiate the establishment of an intermediary organization. This 'service provider' is subsequently equipped with the resources and legitimation needed to directly create or shape system resources.

To conclude while in chapter 2 the theoretical framework of resources at the organizational-, network- and system-level was developed we could show in the empirical chapters (3-5) that system resources are created and shaped and strategically relevant for innovating actors, that formal networks are crucial for system-building drawing on specific (network) resources portfolios and finally, in the chapter 5, that resources at different levels matter for system builders and determine different system-building strategies.

6.2 Contribution to TIS literature

While many TIS studies refer to emergent effects and cumulative causation to explain TIS build-up, we were able to show that strategic moves of actors had a considerable impact on the formation of the TIS of stationary fuel cells. System builders and actors organized in formal networks were deliberately creating and shaping system resources in order to provide positive externalities of many different kinds. We concluded that the coordination of actors and the deliberate creation of value networks and system resources is key to explaining the performance of TIS, especially in an early phase. In this regard our analysis opened up a new perspective on the process of deliberate system-building, in which the strategies of system builders and formal networks, and the concept of resources are essential for the analysis of the formation of TIS.

This perspective complements the current TIS research on system dynamics: deliberate system-building activities could impact emergent system-building processes and vice versa. Moreover, both processes have to be taken into account to better explain the emergence or breakdown of technological fields. However, in order to explore hidden factors which determine deliberate system-building, TIS researchers have to adapt their view on agency and on structural components. Our study complements the existing literature with more elaborate concepts on actors and (formal) networks as well as on resources.

Resources in TIS studies are currently referred to as inputs, such as financial or human capital which are needed for the development of a particular technology (Bergek et al., 2008a,Hekkert et al., 2007). Activities in TIS are analyzed according to how they influence the allocation of such inputs and contribute to the system function resource mobilization (ibid). The resource concept from the field of strategic management complements this view and puts emphasis on strategy making and the opportunity sets (innovating) actors can use to achieve their aims in innovation. Firstly, this perspective helps TIS scholars to recognize the strategic value of TIS components. Technology-specific institutions can be framed as system resources innovation actors can draw upon: they reduce uncertainty and ambiguity and spur the development of a new technological field. Secondly, resources not only facilitate technology innovation but also determine the range of strategic activities that innovating actors (and formal networks) can pursue.[61] Therefore, we also shed light on processes of resource development, for example combination and transformation of resources in formal networks. Additional resource characteristics such as where they were established and who can reap their benefits, are crucial to uncovering agency and the importance of different actors, e.g. in system-building. By differentiating resources at the organizational, network and system level, scholars can now analyze the role of actors, identify important resources provided by networks, and track determinants for deliberate system-building (e.g. barriers for coordination and collective action, e.g. why important actors to not contribute critical resources or why networks do not develop specific networks resources such as trust).

Actors and networks are, according to the perspective we introduced, not only system components but a source of agency in TIS build-up. Until now, actors have been conceptualized only as actor groups with specific roles, while networks have been primarily regarded as informal structures which facilitate knowledge exchange. Our framework extends this view. Firstly, specific actors – so-called system builders – can be differentiated and analyzed in terms of the crucial resources and competences they have at their disposal. System builders play a key role in the coordination of the TIS build-up, creating and shaping system resources, and are thus able to manipulate certain paths of TIS formation. To delineate the actor group of system builders, and to analyze their strategies and resources, is therefore vital in the anticipation of certain paths of TIS development. Secondly, formal networks can also be conceptualized as entities which control and accumulate different kinds of resources as well as pursuing specific strategies. In fact, they are often used for solving TIS deficits and accomplishing certain system-building tasks. By conceptualizing formal networks as organizational structures, TIS studies can better analyze determinants for collective action and processes of coordinated system-building. Thirdly, by analyzing the abilities and resource portfolios of actors and

[61] Subsequently, resources such as common culture, trust, shared goals or reputation also appear as important factors for the successful development of a new technology, next to financial and human resources.

networks, scholars can assess their potentials in system-building, predict certain paths of TIS formation and thus link structural and functional analysis.

6.3 Contribution to strategic management literature

The analysis of resources in emergent technological fields is also beneficial for the literature on strategic management. The relational view deals with resources that span firm boundaries and that are embedded in inter-organizational relationships (Dyer and Singh, 1998). While studies of the relational view analyze resources of strategic alliances, broader networks in the field of emerging technologies have until now not been studied in this way. The co-operation of various actor groups (e.g. firms, associations, local authorities etc.) and the deployment of network resources to shape and create new business opportunities have not yet been the subject of investigation. Subsequently, the study of resources in emergent technological fields opens up an interesting field of study where a broader range of resources at the network and system level is strategically relevant for innovating firms.

In addition we were able to show that firms in technological innovation systems pursue joint strategies to further develop technologies and to build up a supporting entrepreneurial infrastructure (Van de Ven, 1993). The focus is therefore not the competitive advantage of single firms but the survival and success of a novel technology (e.g. in the competition with different variants or incumbent technologies). This is a deviation from traditional thinking in the field of strategic management. Accordingly, firms and other organizations which co-operate and deploy network resources to shape and create their environment may be better off, as they are able to establish business networks, new markets and other supportive institutional structures. The cooperation and co-creation of new markets or technological fields is therefore a strategy which might be of importance for the realization of radical technologies.

Moreover, firms that are able to shape and create their environment through co-operating in formal networks may have advantages when a technological field matures. In other words, their organizational resources might better match the characteristics of the created and shaped technological field (e.g. technological standards, costumer preferences). For this reason, agenda setting, networking and involving other actors through formal networks – managing the collective survival of an emerging technological field – are key competencies in radical innovation and innovation management, and will need further attention in future studies.

6.4 Outlook on future research

In this thesis we have broken new ground in showing how firm strategies and system level processes are intertwined. During the research we touched upon many different theoretical and empirical problems, while new ideas and interesting questions emerged which will guide further research in the field.

6.4.1 Research on resources

This study is a first step towards the integration of insights into the nature of different kinds of resources outside the traditional boundaries of innovating firms, but much work still needs to be done. This includes an enhanced delineation of different types of resources, a better understanding of how they depend on each other (resource complementarities) and how they are used, combined and changed in innovation system-building.

- Technology-specific institutions such as standards or support programs can be regarded as resources, which open up new opportunities for the firms that use them. At the same time, they can constrain innovation and lock-out technological alternatives (Coriat and Weinstein, 2002). In this study it was revealed that it depends on the competitive relationship (e.g. competition between different variants, countries etc.) whether a specific standard is rather a resource or a barrier to innovation. Furthermore, there is a temporal aspect to the impact of institutions: Institutions which facilitate innovation activities in one phase might turn out to be core rigidities (Leonard-Barton, 1992) in a later phase of development: the same resource can have a different value to a firm at different points in time (Mathews, 2002). What affects the value of resources is therefore an interesting question to follow up.
- Resources are often socially constructed and rely on social processes of resource generation and application (Bathelt & Glückler, 2005). In our analysis we found that network reputation, the power a network can exert, or trust between network members are examples of such relational resources. These resources are established through social practices and the interaction of actors in TIS. To better understand agency, and the dominance of certain actors in TIS formation, further research is necessary on the conditions under which relational resources emerge and accumulate as a result of the interplay of different actors in a technological field
- Resources and capabilities have not been fully differentiated and discussed in our empirical analysis. Capabilities might reside at the level of individuals, at the organizational level or at the level of industries (Foss and Eriksen, 1995). For example, how system builders develop capabilities in leadership and agenda setting (Hajek et al., 2011; Möller, 2010), or how they strategically influence the combination of resource portfolios of formal networks, is a relevant issue for future inquiries. As innovation is a long-term process prone to uncertainty and sudden changes, the exploration of dynamic capabilities (Eisenhardt and Martin, 2000; Teece et al., 1997; Wang and Ahmed, 2007) at the TIS level could deliver fruitful results.

6.4.2 Research on strategies

In the literature on strategic management, strategies have often been analysed in established markets or industries (Grant, 1995; Porter, 1980; Porter, 1985). Emerging technological innovation systems provide a context, in which strategies oriented at the wider system and technology (or product) development strategies as such have to be combined.

- In this study the focus has been on strategies, which positively contribute to system-building and support a novel technology. However, we might as well encounter cases, in which firms strategically block the development of an innovation. Incumbent players in an industry, for example, might feel challenged by the new technology and could devise reactive strategies to counteract innovation system-building. Similarly, innovative firms that support competing innovations might engage with one another. From a strategy perspective, it seems to be particularly interesting how pro-active and re-active strategies depend on the resources firms have at their disposal. It is therefore particularly important to pay further attention to how innovating firms can intervene in such situations (c.f. Smink et al., 2011).
- We have elaborated on the strategic reasons firms might have for establishing supportive system resources. It was discussed that firms create and shape TIS in ways that could generate them advantages over their competitors. For instance, firms engaged in TIS build-up have the opportunity to shape market formation or the establishment of the supply-chain in such a way that they will gain future advantages (cf. Musiolik, 2011). We think that a further analysis of the co-creation of organizational and system resources could lead to further interesting results to explain the competitive advantage of firms in emerging markets. First movers might draw on different kinds of advantages during the initiation and co-creation of technology and the subsequent business field. Take, for example, emerging organizational resources like firm reputation (a brand), which might be very difficult for future followers to copy.
- In technology entrepreneurship, the resources needed are often distributed between different actors (Garud and Karnoe, 2003). In our study we found that system-building has a lot to do with activating and integrating complementary actors. Technology-specific suppliers and service providers are crucial to the establishment of new business fields, but it is rather difficult to convince these actors to invest in a new technology, especially in a fast changing environment with high uncertainty. However, it is rather unclear which kinds of strategies system builders have at their disposal for the integration or even for a substitution of these crucial complementary actors (and their resources) to secure technology development.

6.4.3 Interplay of actors

Networks and the interplay of actors in system-building have been key in this thesis. In the empirical study it became clear that in technology entrepreneurship there are times when coordination and the exchange of information and knowledge is strategically intended to activate and integrate actors, and other times when actors are less inclined to allow spill-overs.. In formation phase actors might merely co-operate and, when markets and products are established, the actors start to compete for market shares. Accordingly in different phases of TIS development different modes of interaction might be dominant and influence collective action and system-building.

- On one hand, competition might reduce the willingness of actors to co-operate in system-building. On the other side it may be beneficial for TIS development in general as the concept of development blocks and stimuli suggest (cf. Dahmen, 1988). The same holds true for the degree of technology variety in TIS. When do firms develop a technology on their own and when do they cooperate with potential competitors? In Germany, for instance, manufacturers such as Vaillant and Viessmann did not cooperate to jointly develop a fuel cell heating system. These actors are competitors and did not bundle their forces to be more successful in the long run. They only began to cooperate in the IBZ to create and shape the technological field (cf. chapter 3). Specific constellations of actors in a field might; therefore; hamper innovation, and a coordination of actors might be crucial – especially in terms of global competition and industry policy making.
- In this study, formal networks have been a focal point. Together with informal networks, conferences, fairs and exhibitions they have been explored as a means for establishing an innovation community in new emergent fields (Bathelt and Schuldt, 2008; Lynn et al., 1996; Van de Ven and Garud, 1989). How these different organizational forums interrelate, and how they are used by system builders to shape institutional structures has not been analyzed in greater detail so far. However, we might expect that the formalization of networks is important for the development of a technological field. By increasing knowledge of the interplay of informal and formal networks, policy makers can better support the formation of TIS. In addition, it is to be expected that the characteristics of a technology determine the type of network (regional, national or global) on which the coordination and development of a new technological field depend, and how far support should go. For instance, in the case of fuel cell technology, the NOW GmbH also secured German interests in international (standardization) networks.
- The importance of key actors in steering and initiating collective action was highlighted in this study. However, how such system builders exert leadership, and how they contribute to agenda setting, e.g. by using and influencing expectations in order to steer and lead formal networks, was not analyzed. Moreover, it is crucial that we better understand the transformative capacity of system builders (Giddens, 1984) and the logics that guide them and shape their views, e.g. what constitutes or legitimates objectives in system-building. Capabilities in norm setting, value framing and other forms of leadership within social processes (Hajek et al., 2011) are, in other words, crucial for understanding system-building and

transition processes, and thus require further attention as they guide the activities of complementary actors in the field

6.5 Recapitulation

The emergences of new industries, and a transition of the current energy system towards a sustainable mode of production, are of crucial importance, particularly at times when energy security and climate change issues are closely intertwined with economic development. Clean technologies are currently evolving as components of an alternative, smart and decentralized energy system. In this transition process the field of stationary fuel cells in Germany represents a very interesting case, as the technology is not only important for the development of a smart energy system but also indicative of many technological and organizational problems currently faced by (energy) innovations as they progress from prototypes to a mass market.

Stimulated by energy and innovation policies, electricity market reform and rising energy prices, many firms such as manufacturers or energy service providers have been investing in the development of fuel cells for years now. However, due to the complexity of the novel technology, new types of business relationships and value networks are needed at the supply and the user side. At the same time, guidance (e.g. with regard to standards) and regulatory support are essential. Here we were able to observe many activities involving the coordination, activation, integration and education of complementary actors such as components suppliers, fitters, politicians and so forth. Another key aspect is the creation and shaping of supportive institutional structures such as support programs or the legitimation of the technology.

Again, clean technologies or ‘green industries’ only emerge when suppliers, manufacturers and service providers become interlinked in effective value-chains, and are able turn prototypes into reliable mass products with a competitive price. Here we observed different initiatives of system builders. For example due to the establishment of the VDMA network and creation of the KGP support program suppliers started to adapt established components for fuel cells while fitters were trained in field tests and through created vocational training modules. In addition the NIP support program and the joint field test Callux have been established due to the activities of the IBZ fuel cell initiative. These activities also raise the public interests in the technology and contributed to the creation of a bridging market. In general some key system builder have been able to coordinate the field, to integrate different interests and needs and to jointly shape the National Development Plan Hydrogen and Fuel cells and finally to convince public authorities to support the fuel cells in the NIP support program.

However, there remains work, and fuel cell technology still faces many technological and organizational challenges. Fuel cell manufacturers are currently struggling both to meet the performance standards of conventional heaters and to reach an acceptable price for stationary fuel cells. Still no single firm has the capability to develop core components of fuel cells, such as the Membrane Electrode Assembly (MEA), on its own. Subsequently, before mass production can take place the integration of different competencies, the coordination of value chains and the realization of new business models (e.g. deciding who will assemble and distribute the MEA) still need to be better achieved. In addition, regulations such as guidelines for the connection of micro CHP to the central grid have to be specified, and downstream business models (e.g. fuel cell contracting) have to be developed. In the medium term, joint efforts to achieve subsidies for a market launch program will also be necessary.

The question of whether stationary fuel cells will ever enter the mass market, or if there will be a fuel cell industry in Germany one day, cannot be answered today. However, what we can already see is that in Germany firms and other organizations have been very successful in coordinating and steering the development of a technological field. The set-up of the NIP support program, for example, is a corner stone in this regard.

The case study has therefore contributed to a better understanding of the interplay of technology innovation and the creation and shaping of supportive technological fields. Our empirical insights could be used to reinforce the concepts used in innovation system studies. By better understanding the processes of coordination and system-building, and by introducing a more elaborate resource concept, we now have a more solid foundation for the analysis of the role and abilities of different actors and formal networks in technological innovation. Moreover, the developed framework and knowledge might help to improve the design of public policies and technological support programs, in order to accelerate the market entry of clean technologies and foster the transition of the energy supply system in industrialized societies.

About the author

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Jörg Musiolik was born in Paderborn in Germany, where he also attended secondary school. In 1997 he moved to Marburg to study geography and economics at the Philipps University. These studies gave him the opportunity to deepen his knowledge in the fields of innovation systems and infrastructure sectors. After an exchange year at the University of Stockholm, he graduated in 2004 with the title Diplom-Geograph. His diploma thesis, which analyzed the impact of liberalization and privatization on the organization of public utilities in Germany, was published and awarded a prize at the meeting of German geographers in 2005.

After working as a project assistant at Prognos and completing a trainee-program at the city of Dortmund, he started to work on his PhD in 2008 with the research group CIRUS at the Swiss Federal Institute of Aquatic Science and Technology (Eawag).

During his PhD he has attended a variety of courses and summer schools in strategic management and social science methods (CBS Kopenhagen, HSG St. Gallen, ETH Zürich) and has presented his work at several conferences (Academy of Management 2011, 2nd International Conference on Sustainability Transitions, Dime final conference, Sussex Energy Group conference, DRUID-DIME Academy PhD Conference). Apart from his research and dissemination activities, he has supervised master students, organized scientific workshops and is still engaged in the research community as a reviewer.

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