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Author(s):
Markard, Jochen; Hoffmann, Volker H.

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Analysis of complementarities: Framework and examples from the energy transition

Jochen Markard, Volker H. Hoffmann

Swiss Federal Institute of Technology Zurich, Department of Management, Technology and Economics, Group for Sustainability and Technology, Weinbergstrasse 56/58, 8092 Zurich, Switzerland

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Abstract

Complementarities play a crucial role in socio-technical transitions as they accelerate technology development or decline. Missing complementary components in contrast may hamper the emergence of new technologies or negatively affect sector performance. In this paper, we introduce a conceptual framework to analyze complementarities and to understand their consequences for transitions. Our framework consists of four building blocks: i) different relationships, ii) different components, iii) different purposes and iv) complementarity dynamics. The latter two aspects go beyond existing concepts as they highlight the relative and dynamic nature of complementarities. We illustrate the applicability of the framework with examples from the ongoing energy transition. Finally, we discuss a series of complementarity bottlenecks and potential strategies by firms and policy makers of how to resolve these.

Keywords: Socio-technical transitions, sectoral change, complementary interaction, technological innovation, bottlenecks, public policy

1 Introduction

The study of socio-technical transitions, in which sectors such as energy or transportation change fundamentally and along multiple dimensions, represents a challenge for existing frameworks in innovation studies. One of the issues is that transitions involve changes in a broad range of interrelated technologies. However, not only do technologies change but also the ways in which they

interact and complement each other. Complementary interaction of technical and non-technical components is vital for the provision of services such as energy supply, which is why it is also vital to understand the implications of changes in complementarities in the course of transitions.

Complementarities arise if the value of a combination of specific elements or assets is greater than the sum of the value of each individual element. Complementarities are central for the emergence of novel technologies and the 'functioning' of existing ones (Dahmén, 1988; Van de Ven, 1993). Automobiles, for example, require a network of gas stations, a road infrastructure, traffic and safety regulations, repair shops, specialized suppliers and insurance services. Smart phones require a network of base- and switching stations, interconnectors to landlines and the internet, interoperability standards, different kinds of software, service providers etc.

In the technology and innovation studies literature, complementarities have been associated with a broad range of phenomena, including rapid technology diffusion (Rosenberg, 1976), the emergence of industry standards (Cusumano et al., 1992; van den Ende et al., 2012), development of momentum, path-dependence and lock-in (Arthur, 1987; David, 1985; Hughes, 1987), alliance formation (Dyer and Singh, 1998; van den Ende et al., 2012), strategic technology choice (Kapoor and Furr, 2014) or the survival of incumbents despite being confronted with radically new and better performing technologies (Rothaermel, 2001; Tripsas, 1997). Moreover, complementary interaction of technical and non-technical components is at the core of systems concepts such as large technical systems (Hughes, 1987), development blocks (Dahmén, 1988) or technological innovation systems (Bergek et al., 2008; Carlsson and Stankiewicz, 1991).

In socio-technical transitions, established structures break up, the interplay of system elements changes and so complementarities change as well. In this process of transformation, frictions in the sense of 'structural tensions' (Dahmén, 1988) or 'reverse salients' (Hughes, 1987) may occur: Essential complementary components may be missing or incompatible, technologies may diffuse faster than required complementary infrastructures, and players might be trapped in waiting games (Robinson et al., 2012). Such frictions may not only hamper a transition but they may also trigger further innovation and subsequent changes in how transitions unfold.

The literature on socio-technical transitions[1] acknowledges the relevance of complementarities for explaining the stability and multi-dimensionality of socio-

[1] See Markard et al. (2012) for an overview.

technical regimes (e.g. Geels, 2005b) or when describing key processes for novel technologies to emerge (Bergek et al., 2008; Sandén and Hillman, 2011). In the technological innovation systems framework, system performance is associated with the availability of complementary resources such as human and financial capital, infrastructure, specific products and services etc. Consequently, limitations in the availability of e.g. skilled engineers (Jacobsson and Karltorp, 2012) or natural resources (Wirth and Markard, 2011) have been identified as bottlenecks for the expansion of novel technologies.

At the same time, the transitions literature has not yet explored the dynamics of complementarities, i.e. how they form, change and break up in the course of a transition. Also the consequences of such processes, including the emergence of bottlenecks, require further research. With this paper we make a first step to address these issues. We develop a framework to systematically identify different kinds of complementary relationships with a focus on technologies. The broader goal is to assess bottlenecks that might occur during transitions and to provide insights (e.g. for policy making) of how to resolve these bottlenecks. Our framework has four building blocks: i) different relationships, ii) different components, iii) different purposes and iv) dynamics. We illustrate our framework with examples from the ongoing transition of the energy sector (e.g. Solomon and Krishna, 2011; Strunz, 2014), where new technologies and services emerge and existing ones decline, thus affecting complementarities and creating bottlenecks.

With regard to socio-technical transitions, we argue that complementary and competitive relationships may co-exist, potentially creating trade-offs for the actors involved. We also highlight that time effects (e.g. incompatible planning horizons, strong growth rates in some areas, hog cycles) are important when studying complementarities during transitions.

The article is structured as follows. In section 2, we introduce key concepts, briefly review existing literature and develop our framework. In section 3 we present three examples that illustrate the relevance of complementarities in the energy transition. Referring back to these and other examples, section 4 then compiles bottlenecks and discusses potential relief strategies for policy making. Section 5 concludes.

2 Analyzing complementarities

2.1 Key concepts

A *socio-technical transition* is a fundamental transformation of a socio-technical system (e.g. Geels and Schot, 2010). Such a transition is multi-dimensional, i.e.

it encompasses technological as well as organizational and institutional change. In the course of a transition, new technologies, products, services, organizations, regulations, norms and user practices emerge and existing ones decline. Historical examples of socio-technical transitions are the introduction of pipe based water supply (Geels, 2005a), the shift from cesspools to sewer systems (Geels, 2006) or from carriages to automobiles (Geels, 2005b).

A *socio-technical system* consists of different elements, which include actors (individuals, firms and other organizations), institutional structures (societal norms, technology standards, regulations, user practices, culture, collective expectations etc.), technologies and resources (e.g. knowledge, human and financial capital, natural resources).[2] Large socio-technical systems, which provide services that are of major importance for society, will be referred to as *sectors* in the following. Examples include the energy sector, transportation, agriculture, health care, water supply and sanitation etc.

Complementarity refers to a positive interaction of (at least two) elements, or components, in the sense that the combination yields more value than the sum of the value of each element in isolation (cf. Grandori and Furnari, 2009). Complementarities are at the core of socio-technical systems and they can arise between the same and different kinds of system elements (e.g. firm - firm, firm - resource, technology - institutional structure). Complementarity is closely related to *dependence*: if two element have strong complementarities, they also very much depend on each other (e.g. cars and gas stations). Dependence on a complementary component may lead to *bottlenecks*. A complementarity bottleneck occurs if the performance of a focal element is compromised or hampered because of a complementary component either missing, rare, costly or of insufficient quality.

2.2 Prior research on complementarities

In the literature, complementarities have been studied from different angles and with different research interests. Here we briefly review the contributions associated with technology and innovation in order to identify commonalities.

Scholars interested in technology dynamics coined the notion of *technological interrelatedness* to refer to different products positively influencing each other as they develop and diffuse. Classical examples of interrelatedness include the video recorder (Cusumano et al., 1992) or the DVD recorder (van den Ende et al., 2012), the success of which very much depends on the availability of complementary products such as movies or software. If one type of recorder has

[2] See Geels (2004) for a closely related conceptualization of socio-technical systems.

diffused more widely, film studios or software companies are more inclined to work with the associated format, which leads to increasing returns and the emergence of de facto standards (Arthur, 1987; David, 1985).[3]

Complementarities and interrelatedness are also central features of *system concepts* for the study of innovation processes. Be it socio-technical systems, large technical systems or innovation systems: they are all based on the idea that a large number of different elements including actors and institutions interact closely and in a complementary way (Carlsson and Stankiewicz, 1991; Hughes, 1987; Malerba, 2004; Markard and Truffer, 2008). The technological innovation systems (TIS) concept, for example, highlights that a broad variety of complementary resources (technological knowledge, human resources, venture capital, infrastructures) and institutional structures (common beliefs, expectations, norms and standards, supportive regulation) are needed for novel technologies to emerge and succeed (Bergek et al., 2008). Complementary interaction of system components generates 'positive externalities' (Bergek et al., 2008), strong growth and systems acquiring momentum (Hughes, 1987).

Complementary interaction, however, is just one way of how elements in larger systems influence each other (Sandén and Hillman, 2011). In fact, interdependence would be an overarching term here. The opposite of complementarity is competition, which is about two elements affecting each other negatively. Further modes of interaction include parasitism, i.e. one element having a positive impact on the other, while the other has a negative impact, commensalism, i.e. one element benefits, while the other is not affected or amensalism, i.e. one element is negatively affected, while the other is not affected. Interestingly, these different relationships may even co-exist – depending on the purpose that is in the focus of the analysis. We come back to this in section 2.3.3.

Complementarities are not just relevant for the development of technological fields but also for strategy making at the firm level. With regard to innovation and new products, scholars have highlighted that specific resources and competences, so-called *complementary assets*, need to be combined within and across firms (e.g. Teece, 1986; Tripsas, 1997). These may include technological know-how but also distribution channels, capabilities in manufacturing, access to regulatory bodies or competence in after sales services (Rothaermel, 2001). Industry newcomers typically lack these assets, which is why they have to

[3] Note that interrelatedness is not just confined to products. In the case of the QWERTY-keyboard layout (David, P.A., 1985. Clio and the Economics of QWERTY. American Economic Review 75, 332-337.), the typewriter was complemented by skilled personnel: touch typists and how they learned to write.

collaborate with incumbent players. The incumbent players, in turn, benefit from the innovative ideas and technological competences of the new entrants. This example underlines that complementarities are also a central driver for inter-firm cooperation and alliance formation (Grandori, 1997). Furthermore, complementarities explain why alliances may gain a competitive advantage over single firms (Dyer and Singh, 1998; van den Ende et al., 2012).

Management scholars have also pointed to the necessity of a broader set of organizational and institutional components for the development of new industries (Van de Ven, 1993; Van de Ven et al., 1999). In his *infrastructure for innovation* framework, Van de Ven distinguishes resource endowments (public R&D, financing and insurance, human resources), institutional arrangements (regulations, laws, technology standards), market functions (consumer information, education and demand) and proprietary activities at the firm level like product development and manufacturing (Van de Ven et al., 1999). This is very similar to innovation systems frameworks and the authors also use notions such as community or social system to highlight the collective nature of creating this infrastructure (ibid.).

In summary, complementarities have been studied from different perspectives and while the conceptual frameworks and research interests vary, the basic insights are very much in line: complementarities are central for novel firms, products and technologies to develop, complementarities unfold at different levels (e.g. firm vs. industry) and complementary elements include technologies and products as well as 'non-technical' resources, institutional structures or services. It is also important that many of the above concepts start with a focal element (a firm, a novel product) and view complementary components very much as 'what else is needed for the focal entity to succeed'. In other words, there is a specific *purpose* underlying the identification of complementarities.

2.3 Framework for studying complementarities in transitions

Below we introduce and elaborate on the four building blocks of our framework (cf. Figure 1): i) different relationships, ii) different components, iii) different purposes and iv) complementarity dynamics.

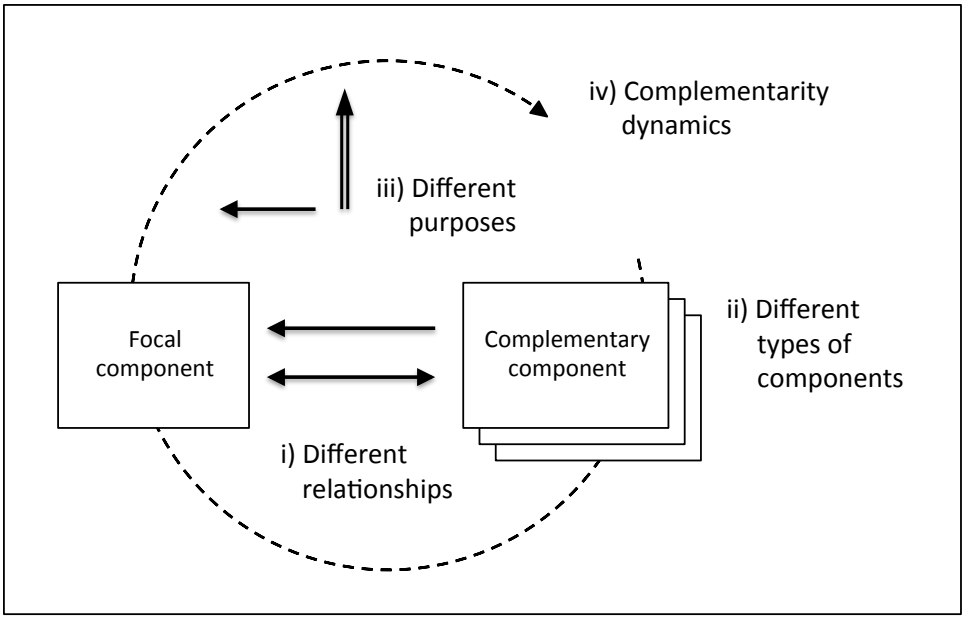

Figure 1: Different kinds of complementarities affect development of focal technology

2.3.1 Different relationships

Complementarity can be unilateral, i.e. one element provides a benefit to the other but not vice versa, or bilateral, i.e. both elements benefit each other, although not necessarily to the same degree (cf. Teece, 1986). Bilateral relationships can play a particularly prominent role in socio-technical transitions as they create positive feedbacks that generate strong or even exponential growth (or performance improvement) in both components.

A second aspect is intensity: complementary relationships can be strong or weak. A strong complementarity exists if a complementary component is crucial for the value or performance of the focal element and non-substitutable. In some cases, complementarity may even be absolute, which means that the complement is strictly necessary for the focal element. An example is that of gas stations for automobiles, or access to clinical trials for pharmaceutical companies developing new drugs. Strong complementarities, which translate into strong dependence, are important with regard to potential bottlenecks (cf. section 4).[4] The intensity of complementarities may change over time, e.g. as technologies become more mature (cf. section 2.3.4).

A third distinction is whether focal and complementary element are different (cars and repair shops, wind power and grid access) or similar (chain links,

[4] Also note that complementarity may be a matter of dose (Grandori and Furnari, 2009) in the sense of an optimum in the availability of the complementary component (e.g. size of a team, density of fuel stations).

cobblestones, firms with similar interests that join forces in standardization). The latter case, which has also been referred to as pooled complementarity (Grandori and Furnari, 2009), is particularly interesting because complementary and competitive relationships may co-exist (cf. section 2.3.3).

2.3.2 Different types of components

The second building block of our framework is a distinction of complementarities according to the types of elements (or components) involved. Given our interest in socio-technical change, we assign technology a central role here as the focal element. This is an analytical choice, given that 'the fate' of a particular technology and of a larger socio-technical system related to the focal technology is of particular interest to transition scholars. Alternatively, scholars that are interested in e.g. a particular firm, or type of firms, might rather choose an organization as the focus of analysis. We expect that our arguments can be translated to other kinds of focal elements as well although modifications might be required.

We distinguish technological, organizational, institutional, and infrastructure complementarities. These types are inspired by the key structural dimensions of technological innovation systems and by Van de Ven's (1993) framework. The distinction of different elements is useful because – in the case of bottlenecks - different actors may be involved and different kinds of intervention strategies may be applicable (e.g. specific innovation policies to address low performance of complementary technologies).

Technological complementarities arise if other technologies positively affect the focal technology. Technological complementarities occur horizontally, where different technologies are combined (e.g. PV power plants and batteries, or natural gas vehicles and filling stations) and vertically, i.e. where they are linked in value chains (e.g. machinery to produce solar cells, batteries as a central component for electric vehicles). Technological complementarities are associated with particular challenges. They often span industry boundaries, which means that different actors, knowledge bases, business models and 'production logics' are involved. Coordination of actors in the different technological fields will therefore be central. Complementary technologies may also display their own dynamics. They may not develop (in terms of capacity and quality) at the same speed as the focal technology or they may be difficult to adapt. To mobilize technological complementarities and to address these challenges, firms may have to deploy different strategies such as backward or forward integration, collaboration and standardization (Musiolik and Markard, 2011; van den Ende et al., 2012).

Organizational complementarities occur if particular types of organizational assets, competences or services positively affect the focal technology. Decentralized co-generation of heat and electricity, for example, has very much benefited from the development of contracting as a new business model for utilities and other firms. Organizational complementarities may occur in all areas of organizational activity (e.g. product development, testing, manufacturing, marketing, distribution, after sales services). Like technological complementarities, organizational complementarities occur horizontally and vertically, i.e. at the same and across different levels of a value chain. Particular challenges can be expected if assets or competences are essential, rare and controlled by specific organizations (e.g. Rothaermel, 2001).

Institutional complementarities occur if specific institutional structures positively affect the focal technology. This will be the case if the focal technology nicely fits into (or has been adapted to) an existing institutional context. Complementary institutions include technology-specific support programs or planning regulations, technology standards, user information and demand, widely shared expectations about the future of a technology etc. Institutional complementarity is often a result of institutional change, which is typically driven by proponents of the focal technology. For example the German feed-in tariff for renewable energy technologies was co-created by NGOs and industry associations from different technological fields (hydro, wind, solar, biomass) and eventually became a backbone for technology development and diffusion (Jacobsson and Lauber, 2006). The formation of institutional complementarities is associated with several challenges, including mobilization of a variety of actors, alignment of interests, overcoming resistance of incumbent actors etc. (Wijen and Ansari, 2007).

Infrastructure complementarities occur if there are generic elements that generate positive effects for a broad range of technologies, including the focal technology. These elements can be universities and research institutes, IPR regulation, political institutions, the legal system, affordable and reliable infrastructure services or various resources (natural resources, skilled personnel, venture capital).[5] Among the four dimensions, infrastructure components tend to be independent of the focal technology in the sense of a unilateral relationship: complementary infrastructure is more like a given background, which is hardly affected by the development of the focal technology. Also note that no clear-cut boundaries can be drawn here, i.e. infrastructure complementarities may overlap with the other three categories.

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[5] These are similar to what Teece (1986) refers to as 'generic assets' or what van de Ven (1993) calls 'resource endowments'.

2.3.3 Different purposes: Technology and sector level complementarities

Complementarities are a matter of perspective, i.e. whether a specific component is complementary to another depends on the underlying *purpose*. In other words, to identify complementarities we first have to specify what the complementary element is supposed to strengthen. Above, we concentrated on a focal technology and defined complementary components as those that positively affect its development. Given our interest in transitions, we now add another perspective as we study the effects of interacting technologies[6] on an entire sector, i.e. on the larger socio-technical system that is transforming.

We distinguish complementarities at the technology and sector level.[7] At the technology level, we assume that creating benefits for a selected technology is the central purpose, e.g. to improve price or performance. Technology level complementarities are those that generate such benefits. At the sector level, we assume that the purpose is to create benefits for the provision of a more general service or societal function[8] such as energy supply, mobility or water supply. Our definition of sector level complementarities therefore reads: elements are complementary at the sector level, if – combined – they better contribute to fulfilling the societal function of the sector than each component on its own. Sector level complementarities can be viewed through the eyes of consumers or – in the case of energy – through the eyes of policy makers or regulatory authorities.

Importantly, with this distinction we may find complementarity and competition co-existing, e.g. two technologies competing at the technology level while being complementary with regard to the sectoral service. In the electricity sector, for example, wind and hydro are competing technologies for power generation. From a sectoral perspective though, hydropower from reservoirs is complementary to wind energy. As wind energy is fluctuating, hydropower is well suited to cover demand in times of low wind and to lower the output when the wind is strong. We find similar examples in transportation. Cars, trains, buses etc. are essentially competing technologies but at the same time, they complement each other in fulfilling our societies' transportation needs.

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[6] We concentrate on technological complementarities in the following.

[7] In Figure 1 we symbolize the different purposes of complementarities by two orthogonal arrows to indicate that technology and sector level complementarities are independent, in principle.

[8] The focus on societal functions is closely connected with the concept of socio-technical regimes, which is at the core of transition studies (e.g. Geels, 2002).

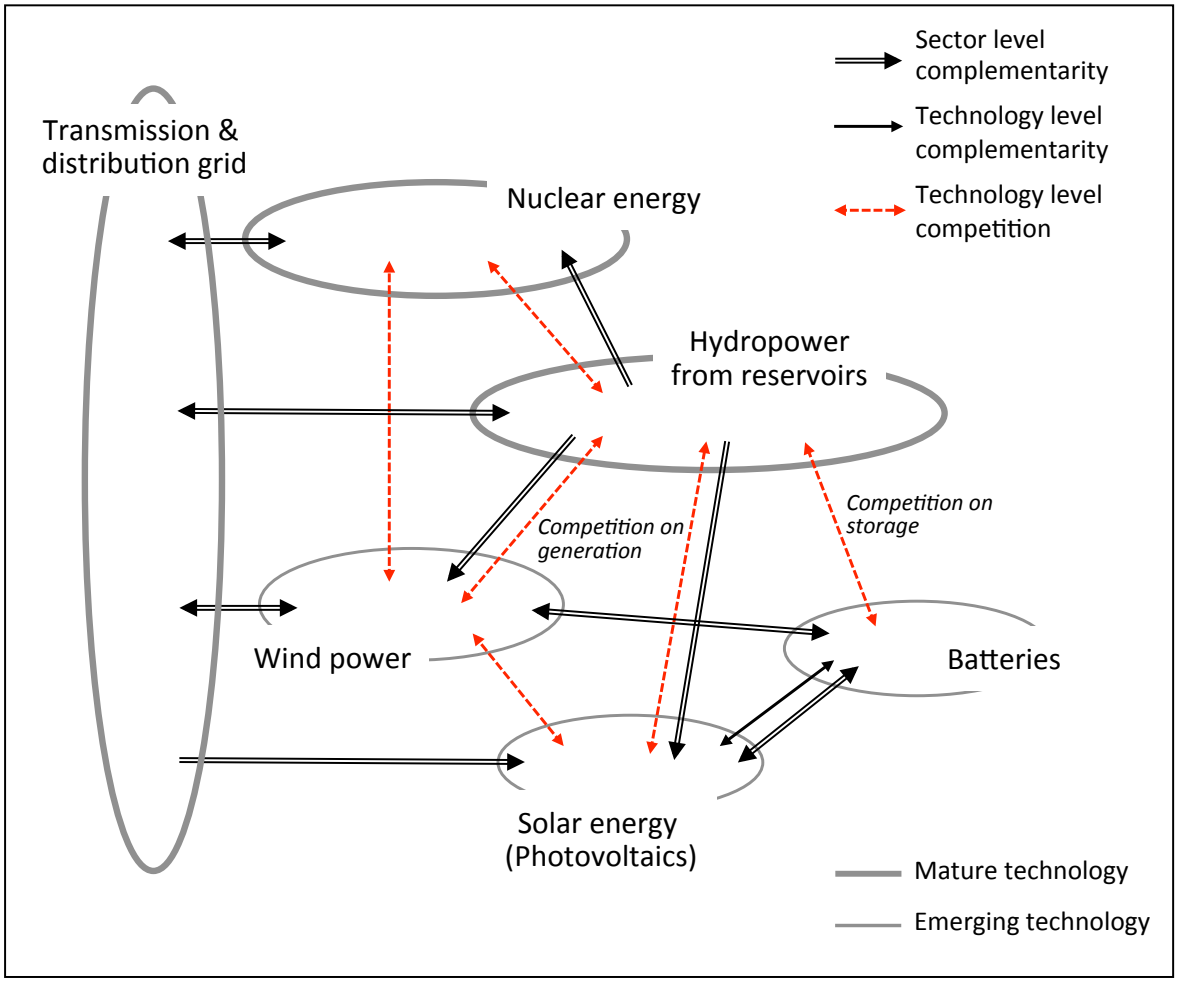

Figure 2: Complementarities and competition between technologies in electricity supply

Figure 2 illustrates the difference of technology and sector level complementarities for a set of key technologies in the electricity sector. There are several complementary relationships at the technology level (e.g. solar and batteries).[9] At the same time, generation technologies (nuclear, hydro, wind and solar) compete at the technology level, and so do storage technologies (hydro and batteries). At the sector level, however, hydropower is complementary to wind, solar and nuclear because it is storable and can cover peak demands, among others. This complementarity is unilateral though because hydro does not need the other generation technologies to fulfill the sectoral demands. On the contrary, it currently even suffers from the success of solar (cf. section 3.1). A similar relationship applies for the grid and solar.

[9] Transmission and distribution technologies play a particular role here, as they are complementary to all generation technologies. Therefore the grid can be viewed as a backbone for the various technologies and the sector as a whole.

The phenomenon that complementarity and competition can co-exist also holds for cases in which the elements are similar (pooled complementarity, cf. Grandori and Furnari, 2009). It occurs where these elements depend on the same inputs or outputs, which are not (yet) available in sufficient quantity or quality and thus have to be created collectively. Renewable energy proponents from wind, solar and biogas, for example, have joined forces to lobby for favorable feed-in regulations or to promote educational programs for renewable energy engineering although they essentially compete for both kinds of resources (Jacobsson and Lauber, 2006). In a similar vein, competing firms in fuel cell technology have formed alliances to advance the field as a whole, e.g. through standardization, education, consumer information, lobbying etc. (Musiolik and Markard, 2011). This again underlines that complementarity is a matter of the underlying purpose. In multilevel settings (firm, technological field, sector) complementary and competing relationships may exist simultaneously. Whether one relationship prevails is also a matter of timing and technology maturity. We will come to this next.

2.3.4 Complementarity dynamics

The fourth building block of our framework is a dynamic perspective. It addresses temporal constraints in the development of complementary elements and changes in complementarities more generally.

Changes take time, regardless of whether a complementary element expands in terms of capacity (more of the same) or improves in terms of performance. Each element of a complementary relationship is characterized by certain constraints, with regard to how fast it can react (shrink, expand, improve etc.). We distinguish elements that can change rather quickly from those with long time horizons that cannot. For example, infrastructures such as roads, canals or power lines typically have a lifetime of decades and also long planning horizons when it comes to expansion or other changes. In a similar vein, if there is a shortage of engineers in an industry or region, it may take years to train new people and to resolve it. For the analysis of complementarities, slow moving elements are of particular importance as they may create bottlenecks for (rapidly) expanding elements. In fact, the challenge is not the slowly (or quickly) changing element as such but different time horizons, or speeds of development.

As a transition unfolds, various elements of a sector change and so do complementarities. In principle, there can be changes in all the aspects highlighted by our framework. Three dimensions, however, seem to be particularly important. First, the directionality of complementarities: unilateral may turn into bilateral and vice versa. Second, the intensity of complementarities may change over time. Third, purposes may change and sector level effects may increase as a technology diffuses and matures.

Such changes of complementarities can be illustrated for the ideal-typical case of a new technology emerging: In early years of technology development, when diffusion is still limited and value chains are yet to emerge, complementarities are mostly unilateral, i.e. the focal technology very much depends on other components. These include other technologies, tailored products and services of suppliers, human and financial resources, etc. In these early times, the technology level is relevant and the sectoral level less so.

In later stages of development, the focal technology will be more abreast with established technologies and has more of an impact. For example, it now constitutes an important market for specialized suppliers thus creating mutual dependence and more of a bilateral complementarity. It will also attract more and more specialized services (e.g. for installation, maintenance, insurance, financing), which will depend very much on the focal technology. At this stage, also sector level complementarities may come into play if the novel technology starts to fundamentally affect the 'functioning' of the sector, altering the interplay of existing technologies.

A maturing technology also constitutes more of a threat to competitors, which is why proponents of different emerging technologies, who joined forces (and thus created complementary effects) against incumbent technologies in early years, may cease collaboration in this phase of development. Above, we already mentioned the example of firms and associations in wind power, photovoltaics and biomass working together for many years to lobby for favorable policy support. More recently though, with each of these technologies becoming more mature and an increasing political debate about the extra costs for renewables' support, common interests weakened and competition between these technologies has come to the fore.

These examples underline the transitory nature of complementarities. Some may persist over long periods of time, while others are more short-lived as the underlying purposes change in the course of a transition. So, when analyzing complementarities, we cannot just look at current relationships but also have to consider potential changes, e.g. by studying time horizons, growth rates, possibly diverging paths of development, emerging bottlenecks etc. We will come back to this in section 4.

3 Examples from the energy transition

In this section, we present and discuss three cases of technologies involved the ongoing transition in energy and transport in order to illustrate the relevance of the different building blocks of our framework. The cases highlight different aspects of complementarities (cf. Table 1). We cannot discuss all

complementarities relevant for each case but highlight those that are associated with different kinds of bottlenecks.

Table 1: Three technology cases and links to framework

Technology	i) Relationships	ii) Components	iii) Purpose: techno-logy vs. sector level	iv) Dynamics
Photo-voltaics	Uni- and bilateral	Different types of components involved	Several sector level complementarities Negative sector level repercussions	Extraordinary growth years Increasing impact as technology matures
Offshore wind	Strong dependence	Organizational complementarity (and monopoly)	Mostly technology level complemen-tarities	Different planning horizons
Alternative vehicles	Critical vs. non-critical complementarities	Mostly technological complementarities	Complementarities between different sectors	Potential future complementarities

3.1 PV: strong growth, sector level complementarities and repercussions

In the electricity sector, photovoltaics (PV) is certainly among the most disruptive new technologies. The technology has seen some impressive growth over the last decade with 177 GW installed as of 2014, covering 1% of the global electricity demand (IEA, 2015). Germany is currently the country with the highest PV generation capacity installed (38 GW). In 2014, 1.4 million PV power plants produced 7% of the country's electricity consumption (Wirth, 2015).

For the case of PV, we highlight three examples of complementarities. The first is about strong growth and potential bottlenecks. From 2006 to 2008, the global PV market grew by more than 400%. As a consequence, existing production capacities in the chemical industry for high-purity silicon (Si), the base input for the dominant PV technology, came to their limits. The scarcity led to soaring prices for PV-silicon, which also affected prices for solar cells. Some PV producers reacted by closing long-term contracts with Si suppliers while others even ventured into Si production to have a better control over this important resource (backward integration). Si scarcity was resolved in subsequent years by a massive expansion of Si production capacity worldwide. This example highlights the consequences of unilateral dependence on a specific resource, aggravated by extraordinary growth of the focal technology.

The second example is about technological complementarities at the sector level. An important rule for service provision in the electricity sector is about demand orientation, i.e. power generation needs to follow demand – anywhere and at all

times. However, generation from PV fluctuates during the day, over the year and with weather. So PV cannot accommodate this rule in isolation but requires complementary technologies. One of these complementary technologies is the electricity grid. It facilitates balancing supply and demand over a larger area and also connects PV to complementary generation technologies such as storage hydropower and gas turbines that can quickly adjust their output when PV is not available. Further alternatives are batteries or other storage technologies. Interestingly, recent technological progress in Li-Ion battery technology meanwhile positively affects PV as both technologies are also sold as a combined product, e.g. to optimize self-consumption of PV-generated electricity.[10]

Another complementary element at the sector level is demand side management (DSM), a purposeful, temporary, remote-controlled reduction or increase of demand to balance e.g. intermittent generation by PV. DSM is a novel service or business. It creates value by controlling large consumption units or by aggregating large numbers of small and distributed units. While both incumbent utility companies as well as newcomers meanwhile test and apply DSM solutions (Strbac, 2008), it tends to be challenging for the former as their engineering-heavy competences are more suited for centralized approaches, i.e. controlling large consumption units. DSM requires experiences in customer relations, marketing, contract management etc. together with extensive competences in information and communication technologies - areas in which energy incumbents are not necessarily strong, traditionally.

The third example is about increasing repercussions when a technology is used more widely (cf. section 2.3.4). In the early years of PV with just some thousand roof-top PV plants, the impact of PV on the sector was negligible. Today, in countries like Germany, where PV accounts for more than 20% of the installed generation capacity, the situation is very different. On sunny days with low demand, PV covers up to 50% or more of the electricity demand, especially around noon. This falls together with a midday peak in demand, which seems to be ideal at first sight. Such peak loads, however, were typically covered by dedicated peak load power plants such as pumped-storage hydro or gas turbines, which means that they now lose a significant part of their former income. This example does not only illustrate changes in complementarities as technologies mature but also points to potentially adverse effects at the sector level: PV currently undermines the economic viability of flexible generation technologies, which in the long run might be needed as a complement to PV.

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[10] For example Tesla motors, a manufacturer of electric vehicles, has just announced to produce and sell stationary batteries for private homes to be combined with PV. https://www.youtube.com/watch?v=yKORsrlN-2k, accessed May 2nd, 2015

So how can we explain this paradox? In the current situation, sector level complementarities (here: positive effects of hydropower for PV, dashed line, Figure 3) are (temporarily) masked by other effects: Among others, PV receives regulatory support through feed-in tariffs (institutional complementarity) that shield the novel technology from a potential loss of the complementarities provided by hydropower. Moreover, another factor complicates the picture: existing base-load power plants (e.g. nuclear or coal-fired) produce a constant output year round, thus covering most times (e.g. nights), in which PV would need to be complemented by hydro. Only if the market share of these base-load plants decreases, peak-load plants might regain an economically attractive position due to their complementarity with PV.

Figure 3 depicts the interplay of PV and some of its complementary elements. Many are at the sectoral level and many complementarities are unidirectional, except those for DSM and batteries, which are bilateral. The circular arrows denote strong growth or progress in a technological field. They may have 'game changing' effects for the focal technology but also for sectoral transformation more broadly. In summary, the PV case illustrates the occurrence of (temporary) bottlenecks due to differential growth in complementary fields, the variety and importance of sector-level complementarities, and increasing repercussions at the sector level as the focal technology matures.

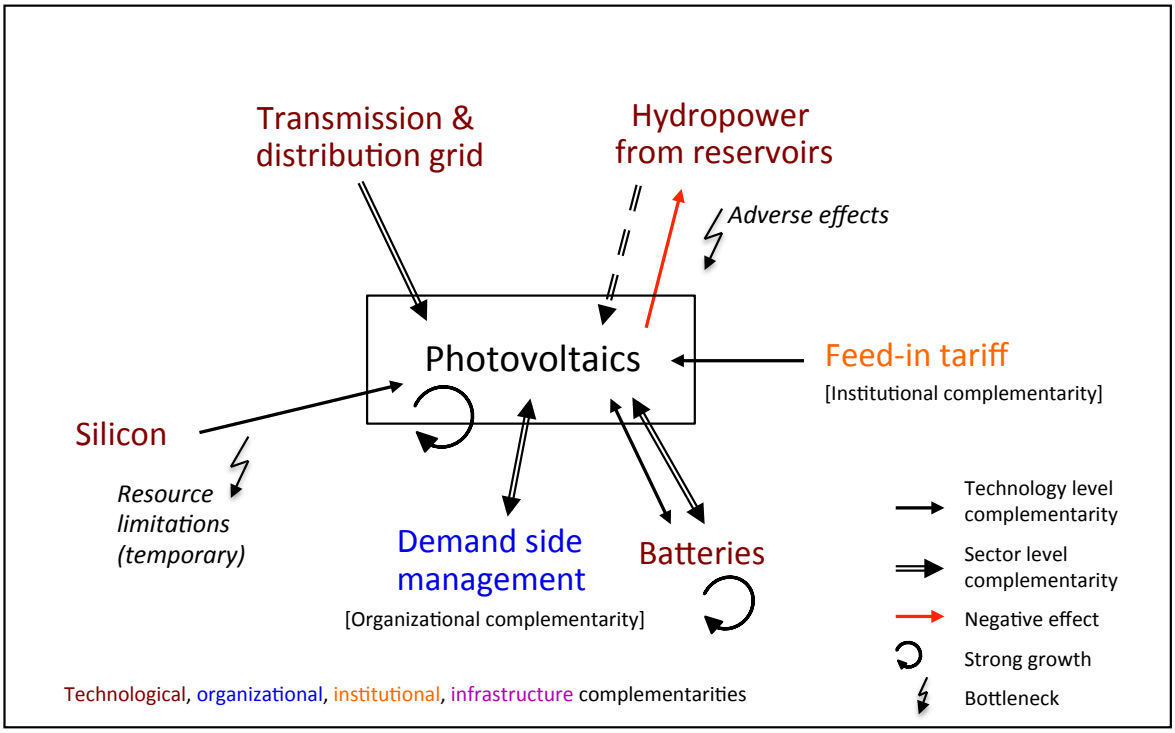

Figure 3: Complementarities in the case of PV

3.2 Offshore wind: absolute dependence, different time horizons and coordination

Offshore wind power is an emerging technology for electricity generation that has large potential for expansion but is still not cost competitive with many fossil and renewable alternatives. By the end of 2014, a generation capacity of 8.7 GW was installed, 90% of it in European waters (GWEC, 2015). Leading countries for offshore wind energy are the UK, Denmark and Germany. Offshore wind currently grows rather steadily with about 1-2 GW per year (ibid.). A key characteristic of offshore wind power is its large project size and associated costs[11], which makes it difficult for small firms or cooperatives to participate in the field (Markard and Petersen, 2009).

Offshore wind power builds on the existing competences and structures in the (onshore) wind energy industry but also depends on a range of special and relatively novel complementary elements at the technology level (Figure 4). These include technical components such as specialized ships, subsea cables, turbine foundations, offshore transformer stations, ports or rotor blade production sites with sea access. Institutional components include specific regulations for marine planning, licensing or environmental impact assessments as well as subsidy schemes for renewables. Also infrastructure components play an important role: specialized know-how in engineering, financial capital and grid connection have been identified as (potential) bottlenecks in the case of accelerated growth in the future (Jacobsson and Karltorp, 2012; Wieczorek et al., 2013).

Here, we elaborate on grid connection because it represents an absolute complementarity: offshore wind parks need to be connected to the electricity grid and thereby to electricity consumers. For this, new transmission lines need to be built, which includes subsea cables as well as onshore lines.

In Germany, grid connection and expansion proved to be a significant bottleneck for offshore wind energy. Even though regulation asked for grid connection within a 30-month period after receiving the concession, actual realization took much longer in several cases.[12] This led to cost overruns and project cancellations. Ready-built wind parks even had to be held in stand-by mode because grid connection was missing.[13] The example shows that complementary

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[11] Four out of nine projects that achieved financial closure in 2014 were above 1 billion Euros (GWEC, 2015).

[12] http://www.wiwo.de/unternehmen/energie/tennet-am-laengeren-kabel/7068090.html, accessed May 3rd, 2015

[13] http://www.spiegel.de/international/germany/german-offshore-wind-industry-goes-from-boom-to-bust-a-914158.html, accessed May 3rd, 2015

components may involve different planning horizons: offshore wind parks can be built within 12-15 months, while grid connection may take 2-3 times longer.

Grid connection also points to the importance of organizational issues, including coordination. One aspect is that grid connection and expansion is a monopoly that is intensely regulated and centrally organized by regional transmission system operators (TSOs), for whom offshore wind is an additional burden. As a consequence wind power operators depend on effective regulation and TSOs cooperating. Cooperation and coordination will be even more critical for plans to realize a European offshore "supergrid", which connects large wind parks in the North and Baltic Sea with each other and with the neighboring national electricity grids (Airtricity, 2006). The realization of such a foundational complementary structure for offshore wind energy represents a major endeavor, as it would require technology providers, utilities, TSOs, investors, authorities and policy makers with different interests and from different countries closely working together.

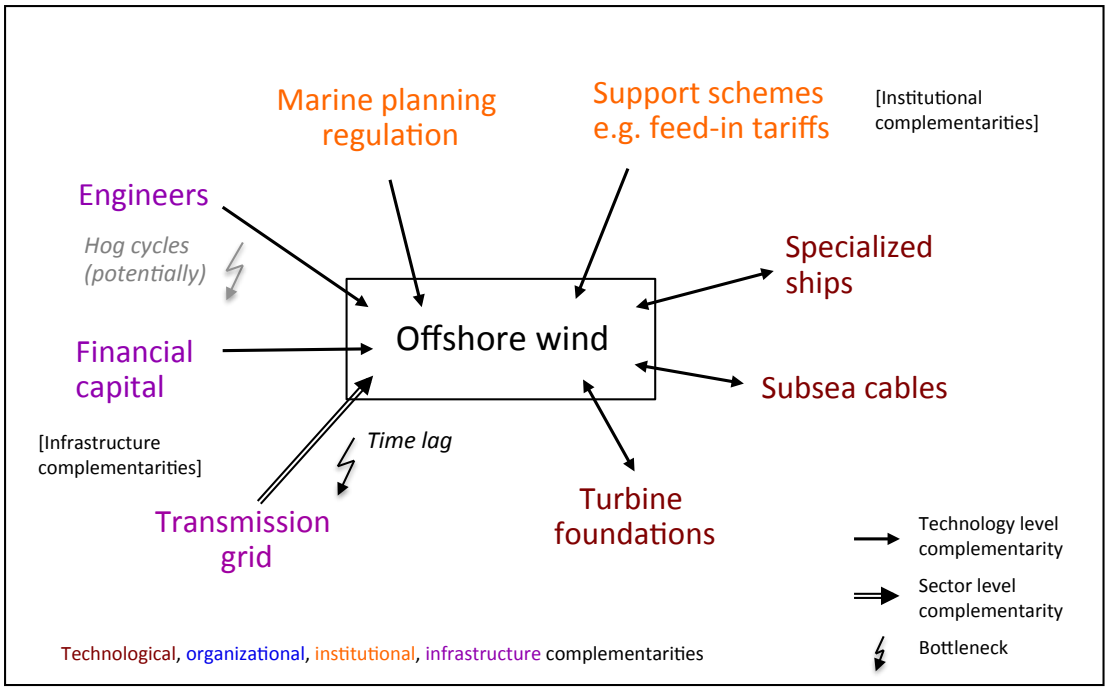

Figure 4: Technology level complementarities for offshore wind

The offshore wind case shows a large variety of uni- and bilateral complementarities at the technology level. It illustrates the challenges of large-scale technology projects, which depend on careful planning and timing – especially with regard to complementary elements, for which dependence is absolute. Where complementary elements take a long time until they are available, they may lag behind the development of the focal technology and create

bottlenecks.[14] Another challenge is that of complementary components controlled by very few or just one organization (here: TSOs). Finally, the offshore case also points to the difficulties that arise if complementarities require the coordinated effort of a large number of actors.

3.3 Alternative vehicles: critical and non-critical complementarities

In the automobile sector, several technological alternatives have been developed with the promise of reduced GHG emissions. These include hybrid electric vehicles, natural gas vehicles, fuel-cell vehicles or electric vehicles. In Germany, Europe's largest automotive market with a stock of 44 million passenger cars, about 85'000 hybrid electric vehicles, 80'000 natural gas vehicles and 12'000 electric vehicles were in operation as of January 2014.[15] Although these alternatives are gaining ground, the sector is still very much dominated by internal combustion engines fueled with gasoline or diesel (Wu et al., 2015).

One of the many obstacles for alternative vehicle technologies is the availability of fueling or charging stations. As of January 2015, there were 920 stations for the refueling of natural gas vehicles in Germany, compared to almost 15'000 'regular' gas stations. For natural gas vehicles, fuel stations represent an absolute complementarity, i.e. their operation fully depends on the availability of specifically equipped stations within driving range.[16] Moreover, the technological complementarity is bilateral, i.e. vehicles depend on the stations and stations depend on the vehicles, and none of the elements is available in sufficient numbers. The result is a *critical* complementarity situation. It creates a dilemma in the sense of a waiting game (cf. Robinson et al., 2012) that can only be overcome by intense coordination: Both technologies need to develop synchronously and with a significant upfront investment.

Also electric vehicles (EVs) depend on a charging infrastructure. However, most of them use the *existing* electricity grid - especially when private owners charge their EV at home. Although charging stations again represent an absolute technological complementarity, the situation is quite different from that of gas vehicles. Complementarity is unilateral, i.e. EVs need the grid but not vice versa

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[14] In case of mutual dependence there might even be hog cycles – a phenomenon often observed where specialized personnel (e.g. engineers), which takes years to educate, is missing.

[15] http://www.autobild.de/artikel/kba-statistik-kfz-bestand-2014-4971719.html, Jan-7, 2015; and number of new electric vehicles admitted in 2014: 8'500

[16] The same holds for fuel-cell vehicles.

and *not critical* because the grid is already widely available and accessible.[17] As a consequence, the diffusion of electric vehicles very much benefits from existing electricity grids.

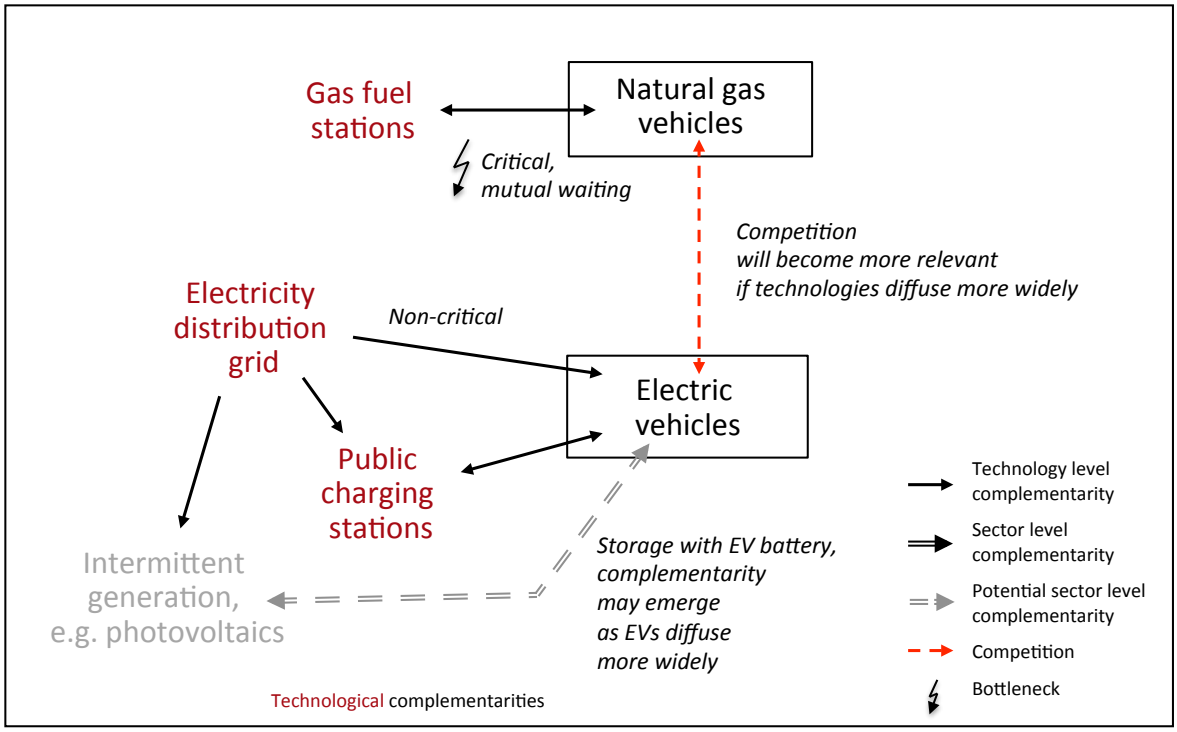

Figure 5: Selected critical and non-critical complementarities for alternative vehicles

The electric vehicle example can also illustrate how complementarities might change as technologies diffuse more widely. In large numbers, EVs will not only compete with natural gas vehicles but also represent a relevant extra load for the electricity grid. At the same time, their batteries may also be used for back-up storage and balancing energy flows, e.g. from intermittent wind or PV power plants.[18] Large electricity companies such as the German RWE but also municipal utilities are conducting pilot projects on the various aspects of electro-mobility, which point to the relevance this emerging technology may have for

[17] Note that this does not hold for *public* charging stations for EVs. They indeed require additional investment, standardization and coordination. But again, also public charging stations benefit from the ubiquitous nature of the electricity grid.

[18] Such applications, however, will again require complementary components such as communication and information technology, distribution grid monitoring, specialized service providers, specific tariffs, contracts with car owners etc.

their business.[19] As a consequence, there will be emerging complementarities at the technology and sectoral level between the electricity sector and transportation.

In summary, the case of alternative vehicles illustrates the difference between critical and non-critical situations. Moreover, it shows that technological complementarities and their relevance might change as a technology matures: A niche technology may not at all affect an existing system, while large scale diffusion may very well do (and require the adaptation of complementary components). This is very similar to the PV case. Thirdly, the example demonstrates that complementarities may well overlap and connect different sectors (here: electricity and transport), which makes the dynamics even less foreseeable especially if radically different technologies are involved. Electric vehicles, in other words, may be a game-changing component for transitions in both energy and transportation.

Our examples have shown that focal technologies are often affected by different complementary relationships, a broad range of complementary components, and complementarities at the sector level. Where complementary components are scarce, lag behind or are not available at all, bottlenecks occur that hamper technology development and transitions more broadly. In the next section, we will therefore look at these bottlenecks in some more detail.

4 Complementarity bottlenecks and implications for policy making

Complementarity bottlenecks can be conceptualized as situations, in which the performance of a focal element is compromised or hampered because of a complementary element. They occur if dependency is strong or even absolute, if there is no substitute and if the complementary element is either missing, rare, costly or of insufficient quality. At the technology level, bottlenecks hamper the development of the focal technology, while at the sector level, bottlenecks are detrimental with regard to the societal function of the sector.

Bottlenecks can appear for several reasons. There might be technological limitations that result in insufficient performance or high costs of the complementary element as in the case of tanks for hydrogen vehicles (Tollefson, 2010). Such weak spots often occur in early stages of technology development. Similar limitations may come from scarce resources, e.g. limited natural

[19] http://www.rwe.com/web/cms/de/183210/rwe/innovation/projekte-technologien/energieanwendung/e-mobility/, accessed May 3rd, 2015

resources for biofuels or biomass combustion (Wirth and Markard, 2011) or silicon scarcity as a bottleneck for PV (cf. section 3.1). A different challenge arises if high upfront investments are necessary for complementarities to unfold. This bootstrapping bottleneck will be particularly critical if dependency is bilateral as in the case of gas vehicles and filling stations (section 0). Another reason might be incompatibility, which is often associated with technological complementarities. Different mobile phone or computer platform standards can serve as an example here (Funk and Methe, 2001).

Bottlenecks also occur as a consequence of time effects, which are particularly important for socio-technical transitions. The example of offshore wind energy (section 3.2) highlighted the challenges that arise due to different planning horizons, or from hog cycles, in which developments in two complementary components are asynchronous due to long reaction times. High growth rates in one element of a complementary relationship as in the case of PV pose a similar challenge.

At the sector level, we find that bottlenecks might even be more complex because many different developments and goals interfere. The adverse effects in the case of PV and hydropower in Germany are an example here. Moreover, there may be so-called persistent problems (Schuitmaker, 2012) due to existing lock-ins that systematically hinder otherwise required changes in critical components (e.g. regulation). Also note that – both at the technology and sector level – bottlenecks may be purposefully created or maintained by incumbent actors that have an interest to block or slow down technological and sectoral change (Smink et al., 2015).

In Table 2 we list some of the bottlenecks associated with complementarities to show the large variety of phenomena and mechanisms at work without claiming to be complete.[20] For each entry we describe the nature (and partly the cause) of the problem, when it typically occurs and how to possibly solve it. We distinguish bottlenecks at the technology and sector level. Note however that the former may equally contribute to problems at the level of the sector.

[20] Among others, we do not discuss how bottlenecks are affected by organizational issues (e.g. who controls specific assets, whether there is intense competition or not, whether strategic interests are at stake) – for the sake of simplicity.

Table 2: Examples of bottlenecks

Label	Problem description	Type of complementarity	When does it occur?	Examples	Countermeasure(s)
Technology level					
Weak spot	Complementary component does not exist or has low performance	Unilateral, typical for technological complementarities	Often in early stages of technology development	Safe, high capacity tanks for hydrogen vehicles (Tollefson 2010)	R&D, innovation, technological breakthrough
Resource limita-tions	Complementary component is scarce (scarcity can be temporarily or spatially limited)	Unilateral, typical for infrastructure complementarities	Temporary scarcity typically occurs in phases of high growth	Si for PV plants (section 3.1) Engineers for offshore wind (section 3.2) Arable land for biofuels Rare earth metals for wind power generators	Monitoring of growth rates, increase of diversity/potential substitutes
Boot-strapping	Each component depends on the other; waiting game	Bilateral, typical for infrastructure complementarities	Typically in early stages of development, critical when upfront investments are high	Gas vehicles and filling stations (section 3.3) Steel industry and railways (Justman and Teubal 1991) Low demand because of low performance No specialized suppliers because of low market volume	Coordinated action, initial investment subsidies
Incom-patibility	Complementary components do not fit together; competing standards	Bilateral, typical for technological complementarities	Often in early stages of development, critical when different actors compete with different designs	Mobile phone standards (Funk and Methe 2001) Standardized plugs for electric vehicles Smart meter standards (Erlinghagen et al. 2015)	Coordination, cooperation in standard development organizations
Time lag	Complementary component lags behind	Unilateral, often for infrastructure complementarities	Typical when planning horizons are long and incompatible	Offshore wind and grid connection (section 3.2) Large infrastructure projects with long planning and realization times	Coordination, regulatory support of lagging component
Hog cycles	Asynchronous development cycles of complementary components	Bilateral	Typical for components with long 'reaction times'; critical in phases of high growth	Offshore wind: bust of auxiliary equipment supply Industry demand for a particular profession and students	Monitoring, diversification

Sector level					
Reverse salient	Low performance of central component hampers sectoral growth	Unilateral	During expansion of socio-technical systems	DC in the early years of electricity supply (Hughes 1987) Copyright institutions for mobile music business	R&D, innovation, technological breakthrough
Adverse effects	Complementary relationship masked by other effects	Uni-/bilateral	Systems in transition	Large-scale PV diffusion affects peak-load power plants (section 3.1)	Monitoring
Persistent problem or lock-in	Change in critical component is prevented by existing structures	Multilateral	Typical for systems with strong multiple interdependen-cies	Carbon lock-in (Unruh 2000) Specialization in medical care (Schuitmaker 2012)	Unlocking strategies

To resolve bottlenecks, actors can pursue different strategies. A general strategy is to 'innovate around the bottleneck' in order to reduce the dependency on a specific component. For example, the focal element can be changed in a way that the low performing complement can be substituted by a different, better performing one to achieve a similar purpose. This strategy, in fact, might lead to further innovation as in the early years of electrification when established direct current (DC) systems proved increasingly incapable of serving ever-growing loads and were finally replaced by alternating current (AC) systems.

In many cases, however, targeting the complementary component is more straightforward. Strategies might then differ depending on the type of complementary components missing: If a complementary technology creates a bottleneck, R&D and innovation strategies that target performance improvements of the complementary component may deliver a solution. If organizational complementarities are lacking, it will be an option to improve specific organizational capabilities, to develop new services or to involve organizations that already have related competences. In the case of institutional complementarities missing, actors will have to engage in institutional work targeting formal institutions (regulation, standards) as well as informal ones (e.g. collective expectations, societal values) through lobbying, framing, negotiation, alliance formation etc. Finally, if infrastructure complementarities are concerned, similar strategies can be deployed but the challenge may be bigger because the potential benefits accrue for a broad range of actors and freeriding might be an issue.

Strategies to resolve bottlenecks can be pursued by different kinds of actors. In many cases, bottlenecks will be identified and counteracted by firms or other

industry actors with an economic interest in the focal technology or product. This has been the case in the PV industry (section 3.1), where high Si-prices spurred private investments into the expansion of production capacities. Similar but more complex are coordinated activities at the industry level, where firms join forces to resolve bottlenecks, e.g. as they develop common standards (Lyytinen and Fomin, 2002), or initiate complementary educational programs for installation and maintenance of a novel technology (Musiolik and Markard, 2011).

Next to industry actors or intermediary organizations, policy makers may play a particular role in facilitating the creation of complementarities and the resolution of bottlenecks. Public policies may be particularly effective in situations, in which cooperation among actors is hindered by conflicting interests, lack of trust, mutual waiting or potential freeriding. Especially infrastructure complementarities that generate a broad range of positive externalities and complementarities, which require high upfront investments, can be expected to benefit from policy support. Moreover, public policies may be needed if incumbent actors strategically obstruct socio-technical change or where existing sectors are very much locked-in into established technologies (cf. Weber and Rohracher, 2012).

Typical domains for policy intervention include science and innovation policy (e.g. addressing weak spots, reverse salient), deployment policies to foster market development (bootstrapping problem), coordination of standardization through standard development organizations or introduction of mandatory standards (incompatibility), public procurement or direct investment to ensure necessary development or expansion of infrastructures (bootstrapping), one-stop-shopping in the case of large projects (time lag), or anti-trust policies to prevent the strategic abuse of critical assets.

While it is beyond the scope of this paper to elaborate on strategies or policies towards the mobilization of complementarities in detail, we can outline five generic tasks. Three tasks are directly related to complementarities and thus follow from our framework:

- Analysis of sector level complementarities: For the development of a specific sector, it is important to identify complementarities and bottlenecks related to the key function(s) of this sector.
- Analysis of technology level complementarities: For the development of a specific technology, it is central i) to identify technological, organizational, institutional and infrastructural components the focal technology depends on, ii) to assess their importance and iii) to identify critical bottlenecks.
- Monitoring of changes in complementarities: It is also necessary to track the dynamics of complementary components at the technology and sector level in

order to identify potential bottlenecks in the future. Do the complementary components develop at a sufficient rate and into the envisioned direction? Are some components lagging behind?

Another two tasks are more fundamental. They relate to questions with respect to larger socio-technical transitions, which motivated our paper in the first place. Moreover, they are a pre-requisite to address the three complementarity-related tasks.

- Formulation of long-term goals for sectoral transformation: What are the key goals of the transformation and what are the central functions and performance characteristics the sector should fulfill?
- Selection of key technologies: Which technologies are regarded as essential for the envisioned transition?

These tasks (especially the last two) are by no means easy to accomplish. During transitions, uncertainty is very high and any assessment of complementarities necessarily incomplete. Moreover, different actors, or actor coalitions, can be expected to prioritize different values and strategic goals, which is why decisions have to be taken amidst conflicting interests (Markard, Suter, et al., 2016; Meadowcroft, 2009). Influential actors will exert power to influence decisions and political goals in their favor, which is why transition policy making processes require particularly careful deliberation (Stirling, 2014).

A related challenge is who can address these tasks. They go well beyond the typical strategic scope of industry actors and we suggested above that policy makers might play a crucial role here. At the same time, they also exceed the capabilities of 'conventional' policy making, because established policy processes were not designed to deal with such complex issues. This is why transition scholars have advocated new policy approaches[21], which mobilize a broad range of societal actors (including different interests and competences) and which are reflexive in the sense that both policies and policy processes can be continuously adapted to deal with unforeseen developments (e.g. Loorbach and Rotmans, 2010; Voß et al., 2009). How to integrate monitoring and 'management' of complementarities into these approaches has to be investigated in subsequent studies. Our paper has provided a first step in this regard as it directs attention to the issue of complementarities and makes suggestions for analyzing them in a systematic way.

[21] Often referred to as transition management or transition governance in the literature (Grin, 2010).

5 Conclusions

Complementarities are a crucial issue for both, the development of technologies and the transition of socio-technical systems. The transitions literature acknowledges complementarities when explaining the rigidity of regimes or processes of cumulative causation in technological innovation systems, but has so far not yet analyzed the specific challenges associated with the re-configuration of complementarities in the course of transitions. We have shown that complementarities can be multi-facetted, creating complex situations with many challenges for the actors involved (e.g. coordination, timing, managing trade-offs). We have also discussed a series of bottlenecks, the reasons behind these and potential strategies for resolution. We think that these will be central for, e.g. industry actors and policy makers interested in the progress of a specific transition.

The main contribution of this paper is a conceptual framework for studying complementarities in the context of socio-technical transitions. It consists of four building blocks: i) different relationships, ii) different components, iii) different purposes and iv) complementarity dynamics. Departing from a focal technology, we have suggested distinguishing uni- vs. bilateral complementarities, strong vs. weak dependency and similar from same components (ad i). Especially the first two aspects are of major importance for how difficult bottlenecks are to resolve. Second, we differentiate technological, organizational, institutional, and infrastructure complementarities (ad ii). By this we highlight that very different kinds of components can play a role and that these may be subject to different domains of influence (e.g. innovation policy, organizational learning, institutional change). Moreover, we direct attention to the complementarities produced by generic resources such as human or financial capital or a 'well-functioning' regulatory environment, which may be difficult to create and manage due to the many positive externalities they generate.

Third, we have distinguished complementarities at the technology and sector level (ad iii). This goes beyond existing concepts because it highlights that complementary depends on the purpose we are looking at.[22] One of the consequences is that complementary and competing relationships can exist simultaneously when different purposes are taken up in the analysis. We have shown that technologies, which compete on one dimension (e.g. power generation), may well be complementary with regard to sectoral service provision (e.g. electricity supply that follows demand at all times). When studying socio-

[22] These purposes are not given but rather subject to social processes, which also means that they might change in the course of a socio-technical transition.

technical transitions, the distinction of technology vs. sector level complementarities is therefore an important step.

Finally, we have highlighted the importance of changes in complementarities (ad iv). In the course of a transition, complementarities may arise or vanish, they may become more or less intense and their directionality may change. The emergence, maturation and decline of technologies is a key driver of why complementarities change but there are also other drivers (e.g. organizational and institutional changes), which will have to be explored in subsequent studies. In the case of biogas in Germany, for example, the primary purpose of the technology shifted over time from solving a waste problem to generating energy, which resulted in a loss of support from earlier, complementary institutions in the agricultural sector (Markard, Wirth, et al., 2016).

With the help of this framework, we then discussed a series of bottlenecks, which might occur in transitions. These include bootstrapping challenges, time lags, persistent problems or adverse effects at the sectoral level, among others. We argued that the resolution of bottlenecks may require coordinated strategies of industry actors as well as public policies.

With regard to strategy and policy making, our perspective highlights a) the importance of an encompassing approach including different kinds of complementarities and different purposes, b) the relevance of attention to the sector level and c) the importance of timing and time frames when devising strategies to reap the benefits of complementarities. Among others, it points to (growth rate) monitoring of complementary components as a tool to identify or anticipate frictions.

Note that the elaboration of intervention strategies will require a thorough discussion of key findings from the literature on innovation policy (e.g. Weber and Rohracher, 2012) and transition management (e.g. Nill and Kemp, 2009; Kemp and Loorbach, 2006). Here, we can only point to the relevance and complexity of complementarities when thinking about public policies that accompany socio-technical transitions.

To conclude, our framework is an attempt to link insights from existing studies on complementarities with the particularities of socio-technical transitions. Further research will be needed to empirically apply, test and improve the framework. In this regard, especially the role of different purposes when analyzing complementarities and the relevance of complementarities at the sector level deserve further attention. We expect that they are very prominent in infrastructure sectors such as electricity or telecommunication, which are not just characterized by a high degree of "systemness" (cf. Markard, 2011) but also by the presence of influential infrastructure complementarities in the sense of backbones for a broad range of technologies and services. It remains to be seen

whether sector level complementarities are of equal relevance for transitions in other sectors such as agriculture or transport.

A related issue is the role of purpose when assessing complementarities. Especially in the case of far-reaching socio-technical change, we cannot assume that the taken-for-granted rules associated with established socio-technical systems (e.g. supply follows demand, high level of quality, security etc.) will live on. On the contrary, these basic rules of regimes may change in the course of a transition and with these the requirements for complementarities at the sectoral (and technological) level. In other words, we cannot determine ex ante which complementarities will become or remain central as a transition unfolds.

Further research may also reach beyond the technological focus of this paper. For example, transition scholars might be interested in studying specific types of firms, or specific resources, and which role e.g. complementary assets or incumbents controlling specific resources play in the transformation (Erlinghagen and Markard, 2012; Farla et al., 2012; Rothaermel, 2001; Smink et al., 2015). While we expect that most of our arguments can also be applied to these kinds of questions, the framework might require modification. The organizational perspective adds another level and another purpose, i.e. the benefit of specific actors. Those actors, for example, that control scarce complementary components benefit from this scarcity while others do not.

Next to such conceptual reflections and enhancements, empirical studies will be needed to reveal further critical complementarity issues and to systematically identify and assess bottlenecks. This then links with existing approaches for the governance of transition, including time strategies (Nill and Kemp, 2009), that can be adapted to also account for the impact of (changing) complementarities.

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References

Airtricity, 2006. European offshore supergrid proposal. Airtricity, Dublin.

Arthur, W.B., 1987. Competing Technologies: An Overview, in: Dosi, G., Freeman, C., Nelson, R.R., Silverberg, G., Soete, L. (Eds.), Technical Change and Economic Theory. Columbia University Press, New York, pp. 590-607.

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., Rickne, A., 2008. Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. Research Policy 37, 407-429.

Carlsson, B., Stankiewicz, R., 1991. On the nature, function and composition of technological systems. Evolutionary Economics 1, 93-118.

Cusumano, M.A., Mylonadis, Y., Rosenbloom, R.S., 1992. Strategic Maneuvering and Mass-Market Dynamics: The Triumph of VHS over Beta. Business History Review 66, 51-94.

Dahmén, E., 1988. 'Development blocks' in industrial economics. Scandinavian Economic History Review 36, 3-14.

David, P.A., 1985. Clio and the Economics of QWERTY. American Economic Review 75, 332-337.

Dyer, J.H., Singh, H., 1998. The relational view: Cooperative strategy and sources of interorganizational competitive advantage. Academy of Management Review 23, 660-679.

Erlinghagen, S., Lichtensteiger, B., Markard, J., 2015. Smart meter communication standards in Europe - a comparison. Renewable & Sustainable Energy Reviews 43, 1249-1262.

Erlinghagen, S., Markard, J., 2012. Smart grids and the transformation of the electricity sector: ICT firms as potential catalysts for sectoral change. Energy Policy 51, 895-906.

Farla, J., Markard, J., Raven, R., Coenen, L., 2012. Sustainability transitions in the making: A closer look at actors, strategies and resources. Technological Forecasting and Social Change 79, 991-998.

Funk, J.L., Methe, D.T., 2001. Market- and committee-based mechanisms in the creation and diffusion of global industry standards: the case of mobile communication. Research Policy 30, 589-610.

Geels, F.W., 2004. From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory. Research Policy 33, 897-920.

Geels, F.W., 2005a. Co-evolution of technology and society: The transition in water supply and personal hygiene in the Netherlands (1850-1930) - a case study in multi-level perspective. Technology in Society 27, 363-397.

Geels, F.W., 2005b. The Dynamics of Transitions in Socio-technical Systems: A Multi-level Analysis of the Transition Pathway from Horse-drawn Carriages to Automobiles (1860–1930). Technology Analysis & Strategic Management 17, 445–476.

Geels, F.W., 2006. The hygienic transition from cesspools to sewer systems (1840-1930): The dynamics of regime transformation. Research Policy 35, 1069-1082.

Geels, F.W., Schot, J., 2010. The dynamics of sociotechnical transitions - a socio-technical perspective, in: Grin, J., Rotmans, J., Schot, J. (Eds.), Transitions to sustainable development. Routledge, pp. 9-101.

Grandori, A., 1997. An Organizational Assessment of Interfirm Coordination Modes. Organization Studies 18, 897-925.

Grandori, A., Furnari, S., 2009. Types of complementarity, combinative organization forms and structural heterogeneity: Beyond discrete structural alternatives, in: Morroni, M. (Ed.), Corporate Governance, Organization and the Firm: Co-operation and outsourcing in the global economy. Edward Elgar, London, pp. 63-86.

Grin, J., 2010. Understanding transitions from a governance perspective, in: Grin, J., Rotmans, J., Schot, J. (Eds.), Transitions to sustainable developmet. Routledge, pp. 223-319.

GWEC, 2015. Global Wind Report 2014 - Annual market update. Global Wind Energy Council, Brussels.

Hughes, T.P., 1987. The Evolution of Large Technological Systems, in: Bijker, W., Hughes, T.P., Pinch, T. (Eds.), The Social Construction of Technological Systems, Cambridge/MA, pp. 51-82.

IEA, 2015. Snapshopt of global PV markets. International Energy Agency, Paris.

Jacobsson, S., Karltorp, K., 2012. Formation of competences to realize the potential of offshore wind power in the European Union. Energy Policy 44, 374-384.

Jacobsson, S., Lauber, V., 2006. The politics and policy of energy system transformation - Explaining the German diffusion of renewable energy technology. Energy Policy 34, 256-276.

Justman, M., Teubal, M., 1991. A structuralist perspective on the role of technology in economic growth and development. World Development 19, 1167-1183.

Kapoor, R., Furr, N.R., 2014. Complementarities and competition: Unpacking the drivers of entrants' technology choices in the solar photovoltaic industry. Strategic Management Journal, n/a-n/a.

Kemp, R., Loorbach, D., 2006. Transition management: a reflexive governance approach, in: Voß, J.-P., Bauknecht, D., Kemp, R. (Eds.), Reflexive Governance for Sustainable Development. Edward Elgar, Cheltenham, pp. 103-130.

Loorbach, D., Rotmans, J., 2010. The practice of transition management: Examples and lessons from four distinct cases. Futures 42, 237-246.

Lyytinen, K., Fomin, V.V., 2002. Achieving high momentum in the evolution of wireless infrastructures: the battle over the 1G solutions. Telecommunications Policy 26, 149-170.

Malerba, F., 2004. Sectoral systems of innovation: basic concepts, in: Malerba, F. (Ed.), Sectoral systems of innovation: concepts, issues and analyses of six major sectors. Cambridge University Press, Cambridge, pp. 9-41.

Markard, J., 2011. Transformation of Infrastructures: Sector Characteristics and Implications for Fundamental Change. Journal of Infrastructure Systems (ASCE) 17, 107-117.

Markard, J., Petersen, R., 2009. The offshore trend: Structural changes in the wind power sector. Energy Policy 37, 3545-3556.

Markard, J., Suter, M., Ingold, K., 2016. Socio-technical transitions and policy change - Advocacy coalitions in Swiss energy policy. Environmental Innovation and Societal Transitions 18, 215-237.

Markard, J., Truffer, B., 2008. Technological innovation systems and the multi-level perspective: towards an integrated framework. Research Policy 37, 596-615.

Markard, J., Wirth, S., Truffer, B., 2016. Institutional dynamics and technology legitimacy: A framework and a case study on biogas technology. Research Policy 45, 330-344.

Meadowcroft, J., 2009. What about the politics? Sustainable development, transition management, and long term energy transitions. Policy Sciences 42, 323-340.

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.

Nill, J., Kemp, R., 2009. Evolutionary approaches for sustainable innovation policies: From niche to paradigm? Research Policy 38, 668-680.

Robinson, D.K.R., Le Masson, P., Weil, B., 2012. Waiting games: innovation impasses in situations of high uncertainty. Technology Analysis & Strategic Management 24, 543-547.

Rosenberg, N., 1976. Perspectives on Technology. Cambridge University Press, Cambridge.

Rothaermel, F.T., 2001. Complementary assets, strategic alliances, and the incumbent's advantage: an empirical study of industry and firm effects in the biopharmaceutical industry. Research Policy 30, 1235-1251.

Sandén, B.A., Hillman, K.M., 2011. A framework for analysis of multi-mode interaction among technologies with examples from the history of alternative transport fuels in Sweden. Research Policy 40, 403-414.

Schuitmaker, T.J., 2012. Identifying and unravelling persistent problems. Technological Forecasting and Social Change 79, 1021-1031.

Smink, M.M., Hekkert, M.P., Negro, S.O., 2015. Keeping sustainable innovation on a leash? Exploring incumbents' institutional strategies. Business Strategy and the Environment 24, 86-101.

Solomon, B.D., Krishna, K., 2011. The coming sustainable energy transition: History, strategies, and outlook. Energy Policy 39, 7422-7431.

Stirling, A., 2014. Transforming power: Social science and the politics of energy choices. Energy Research and Social Science 1, 83-95.

Strbac, G., 2008. Demand side management: Benefits and challenges. Energy Policy 36, 4419-4426.

Strunz, S., 2014. The German energy transition as a regime shift. Ecological Economics 100, 150-158.

Teece, D.J., 1986. Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy. Research Policy 15, 285-305.

Tollefson, J., 2010. Hydrogen vehicles: Fuel of the future? Nature 464, 1262-1264.

Tripsas, M., 1997. Unraveling the process of creative destruction: Complementary assets and incumbent survival in the typesetter industry. Strategic Management Journal 18, 119-142.

Unruh, G.C., 2000. Understanding carbon lock-in. Energy Policy 28, 817-830.

Van de Ven, A.H., 1993. The development of an infrastructure for entrepreneurship. Journal of Business Venturing 8, 211-230.

Van de Ven, A.H., Polley, D.E., Garud, R., Venkataraman, S., 1999. The innovation journey. Oxford University Press, New York.

van den Ende, J., van de Kaa, G., den Uijl, S., de Vries, H.J., 2012. The Paradox of Standard Flexibility: The Effects of Co-evolution between Standard and Interorganizational Network. Organization Studies 33, 705-736.

Voß, J.-P., Smith, A., Grin, J., 2009. Designing long-term policy: rethinking transition management. Policy Sciences 42, 275-302.

Weber, K.M., Rohracher, H., 2012. Legitimizing research, technology and innovation policies for transformative change. Research Policy 41, 1037-1047.

Wieczorek, A.J., Negro, S.O., Harmsen, R., Heimeriks, G.J., Luo, L., Hekkert, M.P., 2013. A review of the European offshore wind innovation system. Renewable and Sustainable Energy Reviews 26, 294-306.

Wijen, F., Ansari, S., 2007. Overcoming Inaction through Collective Institutional Entrepreneurship: Insights from Regime Theory. Organization Studies 28, 1079-1100.

Wirth, H., 2015. Aktuelle Fakten zur Photovoltaik in Deutschland. Fraunhofer ISE, Freiburg, p. 92.

Wirth, S., Markard, J., 2011. Context matters: How existing sectors and competing technologies affect the prospects of the Swiss Bio-SNG innovation system. Technological Forecasting and Social Change 78, 635-649.

Wu, G., Inderbitzin, A., Bening, C., 2015. Total cost of ownership of electric vehicles compared to conventional vehicles: A probabilistic analysis and projection across market segments. Energy Policy 80, 196-214.