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Analysis of complementarities: Framework and examples from the energy transition

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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.

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, 2015) 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-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

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

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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 elements 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 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 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

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

[3] Note that interrelatedness is not just confined to products. In the case of the QWERTY-keyboard layout (David, 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.