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Technological innovation systems: a review of recent findings and suggestions for future research

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Introduction

In recent studies of sustainability transitions, the technological innovation system (TIS) perspective is one of two dominant perspectives (Markard and Truffer 2008). Since its inception in the early 1990s, when TIS were known as 'technological systems' (Carlsson and Stankiewicz 1991; Carlsson 1995), and the later development of the so-called functions approach (Bergek et al. 2008; Hekkert et al. 2007; Johnson 1998, 2001; Johnson and Jacobsson 2001), the TIS framework has reached widespread diffusion among innovation scholars, especially those interested in sustainable transitions.

The technological (innovation) systems framework was developed by a set of Swedish scholars in the late 1980s and early 1990s. The initiative came from Swedish policy makers, who wanted to 'build a better foundation for technology policy' (Carlsson et al. 2010, p. 146). The resulting framework was based on literature on the economics of innovation and new technology, structural change in industries and firms and evolutionary economics, and highlighted the need to analyse both institutional aspects and the competence and interactions of individual actors to understand technological and industrial dynamics (Carlsson et al. 2010).

The functions approach, which is in focus in this chapter, was first developed by Johnson (1998, 2001). The aim was to identify whether various system approaches had a shared understanding of the central processes that contribute to the overall system goal of developing, diffusing and utilizing new products and processes. A first list of such 'functions' was identified through a scrutiny of a broader set of literature on national systems of innovation (Edquist and Johnson 1997; Lundvall 1992; Nelson 1992; Porter 1990), technological systems (Carlsson and Stankiewicz 1991, 1995; Eliasson 1997), industrial networks and development blocs (Dahmén 1987; Håkansson 1990; Lundgren 1993) and large (socio-)technical systems (Bijker 1995; Hughes 1983, 1990). This list was later modified and complemented by literature from political science (Sabatier 1998), sociology of technology

(Kemp et al. 1998), organizational sociology (e.g. Scott 1995) and organization theory (e.g. Van de Ven 1993), to develop the institutional aspects further.

It soon became clear that the functions framework could be used empirically to integrate technology-specific elements with elements from national, regional and sectoral systems of innovation (Johnson and Jacobsson 2001) and to assess TIS performance (Bergek 2002; Bergek and Jacobsson 2003). The first empirical applications were studies of the Swedish renewable energy TIS (Johnson and Jacobsson 1999, 2001), the Dutch, German and Swedish wind turbine TISs (Bergek and Jacobsson 2002, 2003) and the German solar PV TIS (Jacobsson et al. 2004).

After that, the functions approach was taken up by a number of different researchers and research groups, and to date more than 200 papers have been published using the TIS framework as a theoretical starting point. Empirical studies related to sustainable innovation dominate, including e.g. alternative transport fuels and renewable energy technologies. This implies that the empirical results from these studies are highly relevant from the perspective of sustainable innovation, even though the framework was not developed with a sustainability focus specifically in mind.

In the last decade, some successful attempts have been made to take stock of extant TIS literature with regard to conceptual developments and ambiguities (Bergek 2012) and the systemic weaknesses that characterize emerging TISs (Jacobsson and Bergek 2011; Negro et al. 2012a). However, there is no systematic review of the more general empirical findings of the vast number of TIS studies published so far. The purpose of this chapter is to provide such a review and, based on that, identify fruitful theoretical and empirical topics to explore in future research in this field. Most attention is given to studies using the functions approach, since this has been described as one of the most influential conceptual refinements within TIS research (Markard et al. 2012). As part of the review, some conceptual clarifications with regard to the functions framework are also provided.

The TIS framework and the functions approach

This section summarizes the current understanding of the TIS framework and the functions approach, including different perspectives on TIS delineation and the definition of the functions concept. This serves as an introduction and background to the review of the empirical findings in the following section.

The concept of Technological Innovation System (TIS)

The concept of technological innovation system is based on the earlier concept of technological system, introduced and defined by Carlsson and Stankiewicz (1991, p. 111) as 'a network of agents interacting in a specific *economic/industrial area* under a particular *institutional infrastructure* or set of infrastructures and involved in the generation, diffusion, and utilization of technology'– a definition that is also used in most of the reviewed articles.

The actor network and the institutional infrastructure are both dynamic. When a new TIS first emerges, actors enter and form networks and institutional structures are established or adapted (Jacobsson and Bergek 2004). Over time, the structure matures and becomes more stable, but entry and exit of actors can still occur, as can industry convergence with related changes in innovation collaboration patterns (cf. Bröring et al. 2006). It should here be noted that although much of the empirical literature is focused on the emergence of new TISs, the original definition emphasizes the creation of technological novelty, regardless of what phase of development the TIS is in.

The main basis for defining a TIS is a focal technology or product (Bergek et al. 2008; Carlsson et al. 2002; Carlsson 2006), which is in line with the original definition's focus on a particular economic/industrial area. However, the nature and boundaries of the system should be defined in terms of problem-solving networks rather than buyer-supplier relationships (Carlsson et al. 2002). Indeed, with regard to an industry or sector, an analytical distinction can be made between an innovation system, a production system and a distribution-market system, which can be more or less related (Malerba 2002). A TIS is, thus, in itself not an industry, but actors in an industry are usually main players also in the associated TIS(s).

A TIS can also be delineated geographically to a country or a region. However, since technology dynamics are always more or less international in character, a regional or national delimitation might cause the researcher to miss national specificities, important influences from the international innovation arena and shifts in importance of different scales over time (cf., e.g., Coenen et al. 2012; Dewald and Fromhold-Eisebith 2015; Markard et al. 2012). In line with this, some researchers treat national TISs as sub-systems in a global TIS (e.g. Binz et al. 2012; Blum et al. 2015). Others prefer not to delineate the TIS geographically from the start, but instead let system boundaries be determined empirically, based on the degree of coherence of identified networks (cf., e.g., Binz et al. 2014).

However a TIS is delineated, technologically and geographically, the researcher always has to consider external influences on the system. While this was acknowledged already from start, recent contributions advocate even more strongly for taking different context structures and their influence on the focal TIS into explicit account (e.g. Bergek et al. 2015; Edsand 2017; Mäkitie et al. 2018; Stephan et al. 2017).

The functions approach

The functions framework was originally developed to identify commonalities between different system approaches to innovation (Johnson 1998, 2001) and to integrate aspects from national and sectoral innovation systems into the analysis of TISs (Johnson and Jacobsson 2001).

The concept of function was first defined as ‘the contribution of a component or set of components to the overall function of the TIS, i.e. the development, diffusion and utilization of new products (goods and services) and processes’ (Johnson 1998, 2001). Since the approach was sometimes incorrectly associated with sociological functionalism, it was later clarified that functions should be seen as emergent sub-processes of the overall innovation process (cf. Jacobsson and Jacobsson 2014). With small variations, this definition is used in most of the empirical literature.

Over time a second definition has emerged, which describes functions as structure-building processes that explain the build-up and growth of the system rather than its output in terms of product and process innovation (cf., e.g., Andersson et al. 2017; Bento and Fontes 2015a, b; Binz et al. 2016; Hekkert and Negro 2009; Suurs and Hekkert 2009). However, while structure-building is interesting and might warrant further investigation, the current functions have been derived from literature describing what happens in already existing innovation systems and are, therefore, not necessarily well suited for explaining system emergence in structural terms. Moreover, the structure-oriented definition seems to suggest that structure equals performance – a position which was explicitly opposed by the early functions literature (Bergek et al. 2008; Jacobsson and Bergek 2004).

Several sets of functions have been identified and used in empirical analyses. Currently, two lists (with minor variations) seem to dominate the field: one by Bergek et al. (2008) and one by Hekkert et al. (2007), where the latter is based on the former (see Table 1). Although there are many similarities between the two lists, a systematic comparison of how they are applied in the literature reveals important differences in underlying assumptions, definitions and operationalisations (Bergek 2012), which influence what empirical data researchers collect and how they interpret them. I will return to this issue in the review section.

Table 1. Two different conceptualisations of functions (Source: Bergek (2012))

Bergek et al. (2008)		Hekkert et al. (2007)	
Knowledge development and diffusion	Captures the breadth and depth of the current knowledge base of the TIS, and how that changes over time, including how that knowledge is diffused and combined in the system.	Knowledge development	Encompasses R&D and knowledge development in the form of 'learning by searching' and 'learning by doing'.
		Knowledge diffusion through networks	Exchange of information in networks. Includes 'learning by interacting' and 'learning by using' (if user-producer networks are concerned).
Entrepreneurial experimentation	Uncertainty reduction through trial-and-error experimentation with new technologies, applications and markets.	Entrepreneurial activities	Turns the potential of new knowledge, networks, and markets into concrete actions to generate – and take advantage of – new business opportunities.
Influence on the direction of search	The combined strength of factors inducing or pressuring firms and other organizations to enter the TIS and the mechanisms influencing the direction of search within the TIS in terms of competing technologies, applications, markets, business models, etc.	Guidance of the search	Those activities within the innovation system that can positively affect the visibility and clarity of specific wants among technology users. Represents the process of selection among various technological options.
Market formation	The formation opening up of a market space (e.g. nursing markets) and articulation of demand.	Market formation	Creation of protected space for new technologies.
Legitimation	Increased social acceptance and compliance to institutions of the new technology.	Creation of legitimacy/counteract resistance to change	Creation of legitimacy for a technological trajectory by advocacy coalitions putting the new technology on the agenda and lobbying for resources and favourable tax regimes.
Resource mobilisation	Mobilization of competence/human capital, financial capital and complementary assets (e.g. infrastructure).	Resource mobilisation	Allocation of sufficient resources, both financial and human capital.
Development of positive externalities	Development of free utilities in the system, e.g. pooled labour markets and specialized component suppliers.		

Empirical evidence of functional patterns and mechanisms

The aim of this section is to review the findings of published empirical studies using the functions approach to TIS as their main analytical framework. The review focuses on factors and mechanisms influencing TIS functions and a selection of examples and recent references is provided.[i]

As mentioned in the previous section, articles differ in how they define, operationalize and measure individual functions. They also differ in whether the studied countries are pioneers, followers or later entrants trying to catch up, and whether they are industrialized countries, emerging economies or developing countries. Some articles also use the TIS framework to study diffusion of existing technologies rather than development of new technologies. Such differences influence both how researchers interpret the functions and what types of functional mechanisms they identify.

In order to handle these differences, the structure of this section is based on Bergek et al.'s (2008) definition of each function (with some modifications) and the empirical material from the reviewed articles has been rearranged (and in some cases reinterpreted) accordingly. Each section starts with a brief definition of the function in question, to set the basis for the subsequent review, and key differences resulting from different interpretations and empirical contexts are highlighted.

Knowledge development and diffusion

Knowledge development and diffusion are processes that result in a broadening and deepening of the knowledge base of a TIS, sharing of knowledge between actors within the system and new combinations of knowledge as a result of this.

In the reviewed literature, knowledge development is primarily described in terms of research projects and programs of various kinds. These are often publicly funded and executed by universities, research institutes and companies, sometimes in collaboration. There is, however, surprisingly little mention of product development processes, although the up-scaling of plants is mentioned as a challenging development task in studies of, for example, wind turbines and bio refinery technologies (Gosens and Lu 2013; Hellsmark et al. 2016).

Very little information is also provided about the knowledge base of the TIS and how R&D programs and collaborations contribute to that knowledge base. Notable exceptions are Dantas (2011), who describes the development of ethanol technology in Brazil at a quite detailed level and Gabaldón Estevan and Hekkert (2013) who divide the development of knowledge for tile production into sub-fields such as clay extraction and processing, glazes and tile design. The recent use of bibliometric data and patents to map a technology's development over time (Andersen 2014; Andersson et al. 2017; Binz et al. 2012; Corsatea 2014; Gosens and Lu 2013) show great promise in this respect, although such analyses have so far mostly been used to describe inventor networks and quantitative outputs of R&D programs rather than their knowledge contents.

International interactions are mentioned in a few cases. For example, Andersson et al. (2017) describe how actors in the Swedish marine energy TIS participate in international R&D projects and collaborate with universities abroad. In catch-up contexts, the importance of re-design and engineering, technology acquisition (including licensing) from abroad, participation in international projects and collaboration with established, multinational technology suppliers is, however, emphasized (Dantas 2011; Gosens and Lu 2013, 2014).

In the reviewed literature, not much is said about knowledge diffusion – even when it is treated as a separate function. Some articles mention specific organizations that work as links between companies and universities or other companies, stimulating the diffusion of knowledge, technology and best practices within the TIS (e.g. institutes or advocacy coalitions). Others mention conferences and workshops (Eastwood et al. 2017; Goess et al. 2015) and licensing (Gosens and Lu 2014) as mechanisms for knowledge exchange and diffusion. For the most part, however, knowledge diffusion is only mentioned when there are problems in this respect, for example due to lack of collaboration and communication between actors, limited mobility of people or defensive patenting strategies (cf., e.g., Andersson et al. 2017; Cetindamar and Rickne 2017; Gosens and Lu 2014). This is problematic, considering that knowledge diffusion is important in connecting the actors in a system into a network and making it systemic.

In diffusion oriented TIS analyses, knowledge development is often focused on adaptation of technologies from other countries (Agbemabiese et al. 2012; Bento and Fontes 2015a; Blum et al. 2015; Edsand 2017; Tigabu et al. 2015a), with an associated emphasis on absorptive capacity (Cohen and Levinthal 1990) rather than original knowledge development. The importance of international organizations for building such capacity is emphasized in some studies (Edsand 2017; Tigabu et al. 2015c). Knowledge diffusion is interpreted primarily as dissemination of information about the technology to potential users, e.g. through demonstration plants, promotional campaigns or word of mouth, which according to the original framework would rather be seen as market formation mechanisms. Interestingly, diffusion oriented analyses tend to have a somewhat broader view on knowledge than development oriented analyses, including not only technology but, for example, knowledge about natural resources, markets and finance (cf., e.g., Bento and Fontes 2015a; Dewald and Truffer 2011; Edsand 2017; Palm and Tengvard 2011).

Entrepreneurial experimentation

All technological problems cannot be solved through formal R&D, but some have to be worked out through real-world experiments at different scales (Rosenberg 1976). The same applies to other types of knowledge, for example about how to design business models for new technologies. Entrepreneurial experimentation refers to such processes of uncertainty reduction through trial-and-error experimentation with new technologies, applications and strategies.

The empirical evidence related to this function is limited, since many authors –probably because of the label 'entrepreneurial' – associate it with entry or activities by small or new firms. However, in this context, 'entrepreneurial' refers to acting under uncertainty (cf. Kirzner 1997; Schumpeter 1934). This can be done by any type of actor, including established firms.

Examples of entrepreneurial experimentation for the most part refer to pilot or demonstration plants (PDPs) and the exploration of new applications. Although it is not always clear what the main sources of uncertainty are in specific TISs and what PDPs or other efforts contribute with in this respect, some insights have been gained. Some articles mention the importance of testing new technologies under 'real-life conditions' and at sufficient scale before putting them into commercial operation because of product system complexity and the risks involved in integrating new technologies into a larger system (e.g. an electricity grid) (cf., e.g., Andersen 2014; Dewald and Truffer 2011). Some emphasize the importance of experimenting with a variety of technical solutions within the same TIS when there is uncertainty about the benefits and drawbacks of different designs (e.g. Andersson et al. 2017; Gosens and Lu 2014). Some mention that technologies might have to be tested in and adapted to different application and user contexts (e.g. Binz et al. 2012; Blum et al. 2015; Tigabu et al. 2015c) and discuss the importance of PDPs for demand-side learning (e.g. about installation and operation of new technologies) (e.g. Bento and Fontes 2015a; Edsand 2017).

Market formation

Market formation refers to the opening up of a space or an arena in which goods and services can be exchanged in semi-structured ways between suppliers and buyers and includes sub-processes such as articulation of demand and preferences, product positioning (including pricing and segmentation), standard-setting and development of rules of exchange (Lee et al. 2018; cf. also Dewald and Truffer, 2012). It is, thus, a quite broad and complex function.

Considering this complexity, the reviewed TIS analyses seem to give a rather simplified account of market formation, which consists primarily of sales and installation numbers and descriptions of the public policies that have been in place for the technologies in question. Indeed, when explaining the realized market growth (or lack thereof) most studies refer primarily to relative prices compared with available substitutes and various type of market stimulating policies at national, regional or local levels, such as investment subsidies and tax exemptions, price premiums and mandatory installation policies (e.g. quota systems for renewable electricity and blending of biofuels into gasoline and diesel). Some studies also highlight that demand for new technologies can be stimulated by other types of polices, such as quality standards, building codes and EU directives (e.g. Dewald and Fromhold-Eisebith 2015; Fevolden and Klitkou 2017; Goess et al. 2015; Suurs et al. 2010).

While all these types of policies are clearly of importance, especially for sustainable innovation, they alone cannot explain why and how markets form and how buyers and users are guided toward adopting a new technology. This is to some extent recognized in diffusion oriented analyses, which tend to have a slightly broader view on market formation, including for example awareness-raising mechanisms (e.g. field tests, demonstration sites and word of mouth communication between users) and the establishment of installers and after sales services firms (e.g. Agbemabiese et al. 2012; Blum et al. 2015; Tigabu et al. 2015a, c). It is also highlighted Dewald and Truffer's (2011, 2012) detailed study of the German solar PV TIS, which describes how different market segments develop at local, regional and national levels and how the focus of the TIS shifts between segments over time. As a whole, the TIS literature, however, does not provide any detailed understanding of the market formation process.

Influence on the direction of search

Influence (or guidance) of search processes refers to mechanisms that influence in what direction firms and other actors look for new opportunities and to what problems and solutions they apply their resources. It includes mechanisms incentivizing and pressuring them to engage in innovative work within a particular technological field as well as mechanisms determining what choices they make within that field, for example in terms of competing technologies, applications, markets and business models. In the reviewed literature, there is some confusion with regard to whose search processes this function refers to. It should here be noted that this function refers to supply-side actors along the entire value chain, whereas the guidance of actors' decisions to adopt or buy a technology for their own use is regarded as market formation.

Guidance toward entry into a TIS

The main mechanisms inducing actors to enter a TIS are fairly well described in the reviewed literature. First, actors start to explore new technologies and diversify into new fields because of *crises in their current industries or markets*. For example, market instability in the sugar industry induced Brazilian actors to start developing biofuel technologies (Andersen 2015). However, while such crises might explain why actors need to find new opportunities, they do not explain in which direction they choose to search for those opportunities.

Second, actors are induced by *developments in other industries and the general economy*. The oil price shocks in the 1970s is a commonly mentioned event that resulted in efforts all over the world to replace oil as transport fuel and input to energy production through the development of a whole range of alternative fuels and renewable energy technologies. Similar crises with regard to water and wood fuels shortages have also resulted in efforts to develop new technologies (cf. Binz et al. 2016; Tigabu et al. 2015a, c). There are also several examples where the dynamics of related industries induced actors to enter a TIS. For example, the start of the European space program increased German firms' interest in solar PV technology development (Dewald and Fromhold-Eisebith 2015) and the diffusion of wind power and other intermittent sources of electricity induced Danish firms to engage in the development of hydrogen and fuel cell technologies for energy storage and load balancing (Andreasen and Sovacool 2015).

Third, actors – especially companies – may choose to move into a new technology field because of *market growth or the promise of a large market potential*. For example, the growing demand for hot water became a driver for the Chinese solar water heater industry (Goess et al. 2015), potential markets in developing countries increased investments in solar PV technology development in the US (Haase et al. 2013) and domestic wind power market growth induced Portuguese actors from related fields to diversify into this emerging industry (Bento and Fontes 2015b).

Fourth, *national and international policies* influence the direction of search. At the national level, visions, targets and roadmaps for technology development and diffusion induce the entry of various types of actors (e.g. Al-Saleh and Vidican 2013; Andersson et al. 2017; Bento and Fontes 2015a; Eastwood et al. 2017; Gebreeyesus and Sonobe 2012; Haase et al. 2013; Tigabu et al. 2015a), including policy makers at regional and local levels (cf. Haase et al. 2013). Specific government-initiated projects and support systems can also attract attention to an emerging technology field (Cetindamar 2014; Fevolden and Klitkou 2017; Gebreeyesus and Sonobe 2012; Haase et al. 2013), although their design can influence what type of actors are induced to enter (e.g. local content requirements, cf. e.g. Furtado and Perrot 2015). At the international level, EU directives and legislation, the Kyoto protocol and the Californian ZEV mandate are examples of policies inducing entry of actors into a variety of TISs in several different countries (cf. Andersen 2014; Chung and Yang 2016; Haley 2015; Jacobsson and Karltorp 2013). In a developing country context, the international availability of public support also has a signaling effect, although such signals can become blurred if many different technologies are promoted simultaneously (Blum et al. 2015).

Fifth, but much less emphasized than in, for example, strategic niche management, is the role of *joint internal visions* and collective efforts from TIS actors to spread such visions to other actors (for some examples, see Andersen 2014; Goess et al. 2015; Negro et al. 2012b).

What is interesting is that many studies show that guidance is not a one-off thing, but has to be upheld over time – otherwise the interest in the technology will cool off and actors exit the TIS. The mechanisms described above can also very easily start to work in the opposite direction, inducing exit rather than entry. For example, market crises can result in a lack of resources (Fevolden and Klitkou 2017), a perceived lack of market potential or market decline in specific segments can discourage entry or induce exit (Andersson et al. 2017; Dewald and

Truffer 2011; Dewald and Fromhold-Eisebith 2015; Furtado and Perrot 2015; Goess et al. 2015), visions can result in a backlash if they prove to be overly ambitious (Andersson et al. 2017), roadmaps can exclude (and thereby guide interest away from) certain technologies (Dewald and Achternbosch 2016) and policy support can be withdrawn (Fevolden and Klitkou 2017).

Guidance of search processes within a TIS

Mechanisms influencing the direction in which actors deploy their resources within a TIS, e.g. what technological paths they choose to explore, are less well covered in the reviewed literature, but there are some similarities with the mechanisms guiding actors to enter a TIS. Developments in other industries can have an influence on what technologies are developed within a TIS. For example, the large-scale diffusion of renewable energy technologies has induced the electro-technical industry to refocus its development of transmission systems towards HVDC technology (Andersen 2015) and the development of digital printing has resulted in a need to adapt clinker design and manufacturing (Gabaldón Estevan and Hekkert 2013). Moreover, the choice and design of policy instruments can influence which performance attributes suppliers choose to focus on (e.g. cost versus quality) (cf. Gosens and Lu 2013)

The reviewed literature also emphasizes the importance of existing resources, strategies and beliefs (Bento and Fontes 2015a; Dewald and Truffer 2011; Fevolden and Klitkou 2017; Gabaldón Estevan and Hekkert 2013), concrete problems that have to be solved (Binz et al. 2016), existing standards that new technologies have to conform with in order to be accepted and integrated into larger systems (Andersen 2014; Cetindamar 2014; Dewald and Achternbosch 2016) and new standards and dominant designs that are needed to focus the development within the TIS (Andersson et al. 2017; Goess et al. 2015). Compared with the mechanisms inducing entry into a TIS, these mechanisms are described as more stable and path dependent.

Resource mobilization

Resource mobilization refers to the system's acquisition of different types of resources that are needed for innovation to occur, most notably financial resources (capital), human resources (competence and manpower) and complementary assets (e.g. infrastructure).

In the reviewed literature, the mobilization of *financial resources* for technology development and adoption are in focus. In most cases, development has been driven by public RD&D funding from national and international sources, often over long time-periods. For example, Andersson et al. (2017) describe how Swedish public investments in marine energy started in 1976 and are still ongoing. Public funds to support adoption are also sometimes available, for example in the form of low-interest loans and credits (Blum et al. 2015; Dantas

2011; Gebreeyesus and Sonobe 2012; Gosens and Lu 2013; Haase et al. 2013), funding for pilot and demonstration plants (Fevolden and Klitkou 2017) and through development aid programs (Agbemabiese et al. 2012; Gosens and Lu 2013).

Private funding is rarely explicitly mentioned, but there are some examples in the reviewed studies of investments by large, incumbent firms (cf. Andersson et al. 2017; Bento and Fontes 2015a; Chung and Yang 2016; Dewald and Achternbosch 2016; Fevolden and Klitkou 2017) and investment firms (cf. Andreasen and Sovacool 2015; Bento and Fontes 2015a; Gosens and Lu 2014). In some cases, private funding is described as more cyclical and sensitive to market downturns and financial crises (cf. Fevolden and Klitkou 2017; Gabaldón Estevan and Hekkert 2013; Gosens and Lu 2014) and it seems like it can be more difficult to attract private investors than public ones, especially for small companies (cf. Agbemabiese et al. 2012; Goess et al. 2015; Gosens and Lu 2014).

With regard to the mobilization of *human resources*, university education is one of the main mechanisms mentioned in the reviewed articles (e.g. Andersson et al. 2017; Andreasen and Sovacool 2015; Edsand 2017; Goess et al. 2015), but in many studies practically oriented vocational education and training programs are described as even more important, especially for the development of the supplier industry and especially in developing country contexts (Agbemabiese et al. 2012; Andersen 2015; Blum et al. 2015; Eastwood et al. 2017; Gabaldón Estevan and Hekkert 2013; Gebreeyesus and Sonobe 2012; Gosens and Lu 2013; Tigabu et al. 2015a, c). Few details are, however, provided on what types of competences and skills are required in different TISs, which makes it difficult to identify any common patterns.

Physical resources, such as R&D laboratories, test facilities and infrastructure (e.g. power grids), are only mentioned in a few studies. Some articles focus on identifying missing physical resources, whereas others describe how existing resources can sometimes be exploited by a new technology (Andersson et al. 2017; Gebreeyesus and Sonobe 2012; Haley 2015) and sometimes are incompatible with it (Haase et al. 2013). Interestingly, several cases of physical resources mobilization concern resources not directly related to innovation, e.g. land resources, production facilities or transmission grids (e.g. Al-Saleh and Vidican 2013; Audouin and Gazull 2014; Bento and Fontes 2015a; Chung and Yang 2016; Edsand 2017; Eleftheriadis and Anagnostopoulou 2015; Furtado and Perrot 2015).

Legitimation

Legitimation refers to the process of the new technology, its proponents and the TIS as such achieving regulative, normative and cognitive legitimacy in the eyes of relevant stakeholders, i.e. increasingly being perceived as complying with rules and regulations (legal behaviour), societal norms and values (morally acceptable behaviour) and cognitive frames (expected behaviour). This can involve adaptation to existing institutions, changes in existing institutions or the development of entirely new institutions.

The picture that emerges from the review is quite diverse. There are apparently many ways to interpret legitimacy, both in terms of what is legitimated and in terms of who grants that legitimacy. With regard to the first of these two issues, there are two main interpretations. The most prominent one is *legitimation of the focal technology*. Here, it is evident from the studies that technology legitimacy is closely connected to the perceived benefits of a new technology (in different dimensions) compared with alternative solutions (e.g. Andersen 2014; Andersson et al. 2017; Andreasen and Sovacool 2015; Blum et al. 2015). However, in early phases of development several studies find that the uncertain function and performance of new technologies make stakeholders question their value and ability to provide a solution to current problems (Agbemabiese et al. 2012; Andreasen and Sovacool 2015; Binz et al. 2012; Eastwood et al. 2017). This implies that demonstration and trials that confirm performance, or even a few years of experience with a technology without any apparent problems, can be important legitimation mechanisms (Bento and Fontes 2015a; Binz et al. 2016; Haley 2015), but also that disappointing results from early experiments and technical problems associated with early products can have delegitimising effects (Eastwood et al. 2017; Edsand 2017; Fevolden and Klitkou 2017; Goess et al. 2015; McDowall et al. 2013; Rogers 2016). Confirming the technology's performance through independent assessments by experts and scientists is also legitimating, but lack of evaluation standards and mistrust in experts might limit the effects of such efforts (Andersson et al. 2017; Binz et al. 2016; Vergragt et al. 2011).

A second interpretation is *legitimation of the industry supplying the focal technology*. In established industries, such legitimacy has been built up over time and can have its foundation in the provision of wealth and employment (Gabaldón Estevan and Hekkert 2013). However, such legitimacy can be questioned as new problems emerge, for example related to environmental or health issues, or if the economic relevance and visibility of the industry is limited (Dewald and Achternbosch 2016; Gabaldón Estevan and Hekkert 2013). Emerging industries, which generally lack legitimacy, can gain status and prestige through mechanisms such as certification, local anchoring and the founding of industry associations (Bento and Fontes 2015a; McDowall et al. 2013; Tigabu et al. 2015a, c).

With regard to the second issue, two main stakeholder groups are put forward in the reviewed studies. According to some studies, *the general public and local residents* sometimes oppose certain projects or entire technology fields, for example because of a perceived impact on their health, safety or general well-being (e.g. Andersen 2014; Binz et al. 2016). They, thus, have to be convinced of the advantages of the technology (as discussed above). In addition, the technology's acceptance by *policy makers* is important, both in order for it to receive support and because government involvement in itself signals legitimacy to other stakeholders (cf. Andreasen and Sovacool 2015; Bento and Fontes 2015a; Blum et al. 2015).

Finally, it should be noted that several articles seem to associate legitimation with industry associations and special interest groups, which lobby for the attention and support of policy makers for a technology or industry (cf., e.g., Binz et al. 2012; Dewald and Truffer 2011; Gebreeyesus and Sonobe 2012; Goess et al. 2015; Haase et al. 2013; Tigabu et al. 2015a). However, how lobbying influence technology or industry legitimacy is seldom described in much detail.

Development of positive externalities

Development of positive externalities refers to the creation of system-level utilities (or resources), such as pooled labour markets, complementary technologies and specialized suppliers, which are available also to system actors that did not contribute to building them up.[ii]

Since most of the reviewed articles do not include this function and most studies concern TISs in an early phase of development, where positive externalities usually have not emerged, there is little evidence of mechanisms driving this function. Nevertheless, some relevant aspects can be derived from the empirical accounts. In some cases, the emergence of innovation intermediaries (Howells 2006) is described as important, for example contributing to the diffusion of best practice or coordinating other actors (Andersen 2015; Binz et al. 2016; Gebreeyesus and Sonobe 2012; Tigabu et al. 2015c). This creates opportunities for other actors to access highly specialized knowledge without having to make the required investments themselves. The importance of building up a complete value chain around the focal technology is also highlighted in several studies (Andersen 2014; Bento and Fontes 2015a; Eastwood et al. 2017). An interesting observation in relation to this is that much of this is not directly related to the innovation system, but rather to the production and consumption system, e.g. assembly firms, repair and maintenance shops and logistics firms (Andersen 2015; Gebreeyesus and Sonobe 2012; Gosens and Lu 2014). This seems to indicate that even though a TIS is not an industry, the performance of a TIS can be dependent on industrial development.

Discussion

When reviewing the empirical literature, two issues warranting special attention were identified. First, the interpretation and operationalization of some functions has resulted in a limited understanding of the mechanisms behind them. Second, the functions framework in its present design is perhaps not equally well suited for all types of contexts.

What functions do we need to understand better?

The functions that are most well described in the empirical literature are undoubtedly ‘knowledge development (and diffusion)’, ‘influence on the direction of search’, ‘resource mobilization’ and ‘legitimation’. The reviewed articles provide a fairly good understanding of the mechanisms behind knowledge development and actor entry, especially in emerging TISs, as well as the mobilization of financial resources for knowledge development and adoption. The main weaknesses with regard to these functions are that the knowledge bases of the TISs are often not described in any detail and that knowledge diffusion mechanisms are understudied; that the importance of human and physical resources is downplayed; and that mechanisms guiding the direction of search within a TIS are not very well understood. The two latter would, presumably, be especially relevant for mature TISs, where existing resources and path dependency have been shown to be able to both drive and block endogenous innovation (Onufrey and Bergek 2015; Onufrey 2017). ‘Legitimation’ has been rather well covered, but there is some confusion with regard to what is legitimated (technology or industry) and by what stakeholders (the general public or political decision-makers). Some clarification is, thus, needed.

The functions ‘entrepreneurial experimentation’, ‘market formation’ and ‘development of positive externalities’ are more problematic. With regard to ‘entrepreneurial experimentation’, the misunderstanding regarding the intended meaning of ‘entrepreneurial’ has resulted in a lack of attention to processes of uncertainty reduction through experimental learning. More research is therefore needed to understand what the main sources of uncertainty are and what role experimental learning plays in handling these.

With regard to ‘market formation’, there is too much emphasis on sales and installation numbers and too little on the mechanisms through which markets form. Moreover, relative prices are over-emphasized at the expense of mechanisms such as awareness creation, demand articulation and product positioning. It should also be noted that a number of articles study the formation of the market for the end product (e.g. alternative transport fuels), which can experience quite different dynamics than the TIS’s primary market (e.g. the market for new technologies to produce those fuels) with regard to, for example, economies of scale and experience and other sources of increasing returns to adoption (Arthur 1989; Young 1928).

Finally, ‘development of positive externalities’ is poorly understood, both because it is excluded in several articles and because later development stages are understudied in the literature. Since it plays an important part in understanding what makes a system truly systemic, more attention should be given to it in future work.

In order to remedy the abovementioned weaknesses and truly understand functional dynamics, causal mechanisms have to be established between what happens in a TIS and its environment and its effect on the functions – in each case. This is difficult to achieve using quantitative indicators and events analysis, in which each function is associated with certain indicators or types of events, without considering what actual effects they have in individual cases.[iii] Detailed qualitative data are, thus, required, which can only be derived from thorough case study work.

Does one size fit all?

The review reveals that the functions approach has been applied to two types of contexts that are somewhat different from the context which it was first developed for: diffusion of innovation and developing countries (and often a combination of these).

The diffusion context

It was early on suggested that the TIS approach can be useful to study diffusion (Carlsson and Jacobsson 1993; Jacobsson and Johnson 2000). However, neither of these articles discussed pure diffusion, i.e. without any technology development taking place within the focal TIS, and neither used the functions approach.

Although development and diffusion are closely related, diffusion oriented analyses often run into trouble when trying to distinguish between, most notably, 'market formation', 'influence on the direction of search' and 'resource mobilization', since most of what is included should, in principle, be assigned to the market formation function in the original framework.

This indicates that the current functions framework might be less well suited to study diffusion. A distinction between innovation systems and diffusion systems might, therefore, be useful (in line with Malerba's (2002) abovementioned distinction between innovation systems, production systems and distribution/marketing systems). However, more research is needed to establish the structural and functional characteristics of diffusion systems.

The developing country context

Geographically, a small number of European countries dominate the reviewed studies. The geographical scope has, however, been widened in recent years and now also includes developing countries and emerging economies. Several articles emphasize the differences between these countries and industrialized countries and suggest that the functions framework has to be adapted to be useful also in this context.

In particular, it is argued that developing and emerging economies are more fragmented and lack an established knowledge infrastructure and that they are more context-dependent but also more dependent on developments at the local level (cf., e.g., Blum et al. 2015; Dantas 2011; Edsand 2017; Tigabu et al. 2015a, b, c). Functionally, this implies that building up domestic absorptive capacity and adapting technologies acquired from outside the TIS can be more relevant than traditional R&D in relation to 'knowledge development and diffusion'. Functions such as 'knowledge absorption' (Blum et al. 2015) and 'knowledge accumulation' (Dantas 2011), which include a wide variety of processes related to the acquisition, implementation and use of existing and new knowledge, have been suggested for that purpose. These are interesting approaches, which also have the potential to enrichen traditional TIS studies and cure some of the current weaknesses related to the 'knowledge development and diffusion' and 'entrepreneurial experimentation' functions, as discussed above.

Conclusions and suggestions for further research

This chapter described the TIS framework, with an emphasis of the so-called functions approach, and reviewed the findings of the extant empirical literature regarding functional patterns and mechanisms. Since most of these studies concern the development and diffusion of different types of technologies for the production of renewable energy and transport fuels, these findings should be relevant to sustainable innovation. However, since there are few studies of technologies that are not at least framed as sustainable, it is difficult to say if sustainable innovation differs from innovation in general with regard to functional patterns and mechanisms.

The review of the empirical literature showed that while some functions have been rather well covered in the literature and are rather well-understood, some gaps remain. In particular, a detailed understanding of the underlying mechanism of the functions 'entrepreneurial experimentation', 'market formation' and 'development of positive externalities' is largely missing. It was suggested that the field needs to move beyond the use of indicators to more in-depth, qualitative analyses to be able to establish causal relationships between events and functional processes.

Finally, the framework's applicability in the contexts of diffusion and developing countries was discussed. It was suggested that while some adaptation of the framework to suit the latter context would most likely be fruitful and also has the potential to strengthen the TIS framework in general, the former would perhaps be better studied using a framework focused specifically on diffusion systems (as distinguished from innovation systems).

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[i] A complete list of reviewed articles is available from the author.

[ii] In economics, a positive externality is a benefit that results from a transaction between two parties, which also can be enjoyed by third-party actors that have not paid the full cost of it.

[iii] For example, a common practice is to assign pilot and demonstration plants to 'entrepreneurial experimentation', even though they in many cases would rather contribute to 'knowledge diffusion' or 'market formation' (as evidenced by other empirical studies).