RADAR PAPER 2014

TIS interactions with technological, sectorial, political and geographical contexts: some lessons for analysts*

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- Report elaborated in the context of EIS - Strategic research alliance for Energy Innovation Systems and their dynamics. EIS is funded by the Danish Council for Strategic Research, the Programme Commission on Sustainable Energy and Environment and by the participating research institutions. Info: www.eis-all.dk.

Abstract

This paper takes its departure in criticism raised against the technological innovation system (TIS) literature for neglecting interactions between individual technologies and wider contexts in analyses of socio-technical (sustainability) transitions. We show that the TIS framework have always included contextual aspects but acknowledge that it can be strengthened by a more explicit and developed conceptualization of TIS-context interactions. We propose a conceptual framework which includes four external structural dimensions: technological, sectorial, political and geographical. For each of these, we provide examples of interactions with a focal TIS, identifying issues of relevance to analysts. Lessons for analysts are elaborated on in the concluding discussion.

Key words: technological innovation system, context, interaction, sector, geography, politics, transition

1. Introduction

System approaches to understanding the dynamics of new technologies and industries have gained prominence in academic literature and policy-making in the past decades (Chang and Chen, 2004; Sharif, 2006). These have proven to be instrumental for gaining understanding of industrial dynamics and for informing pressing public policy problems related to national economic competitiveness, regional industrial revival and environmental sustainability.

The specific variant of technological innovation systems (TIS) is an analytical framework that has been used to analyse industrial dynamics in a range of technological fields (Carlsson, 1995, 1997, Jacobsson and Bergek, 2004, Hekkert et al. 2007, Markard and Truffer 2008, Bergek et al. 2008). These include emerging industries in clean-tech sectors, where a building

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block has been added to sustainability transitions research (Markard et al. 2012) by contributing with both a conceptual framework and advice to policy makers (Alkemade et al., 2011; Jacobsson and Karltorp, 2013; Smits et al., 2010; Weber and Rohracher, 2012; Wieczorek and Hekkert, 2012).

As TIS became more widely adopted, it was also contested. Much of this concerned a perceived myopia of TIS and lack of inclusion of structure. It was argued that (i) "…the actual success of innovation is mainly regarded as a consequence of the performance of the innovation system itself. As such it is 'inward looking'… TIS tends not to highlight the interplay between the wider selection environment … and internal system dynamics" (Smith and Raven, 2012, p. 1029); (ii) the functions approach downplays the importance of system structure (Geels, 2011) or (iii) even substitutes for an analysis of social and institutional structures (Coenen et al., 2012) and (iv) it has an underdeveloped understanding of geography (Binz et al., 2012).

Part of this critique reflects a misreading of the TIS literature while some may be a consequence of knowledge underlying the framework being "taken for granted" and not made explicit (Jacobsson and Jacobsson, 2014). Yet, there is also substantive critique reflecting genuine weaknesses of the analytical framework. The purpose of this paper is, therefore, to make the TIS framework more explicit and to improve the conceptualisation of how TIS interacts with its context, strengthening to framework as a tool for analysts.

We begin by correcting some misrepresentations of the conceptual core of TIS studies by explaining where the framework came from and how contextual factors were taken into account in early versions of the TIS approach. In section 3, we make some initial remarks regarding the improvement of the conceptualisation of TIS contexts and interactions. Section 4 demonstrates how technological, industrial, political and geographical contextual structures may interact with internal TIS dynamics. For each of these structures, we provide some inroad to the literature and empirical examples of interactions, identifying issues of relevance for analysts. Section 5 concludes the paper by discussing lessons for analysts.

2. Origin of the approach

The late 1980s saw the emergence of innovation system concepts with different delineations. Systems at the national level (NIS) were analysed by e.g. Freeman (1987) and Lundvall (1992) whereas Asheim and Isaksen (1997) and Cooke et al. (1997) delineated the system from a regional perspective (RIS). Breschi and Malerba (1997) and Malerba (2002) put forward a sectorial approach (SIS) and Carlsson and Stankiewicz (1991) developed a framework which was the start of work on TIS.

The Swedish Board for Technical Development (STU) initiated the work that led to the TIS framework. The objective was to develop an understanding of technical change that could meet the operational needs of STU in designing policies geared towards specific technologies or industries, i.e. the focus was on *selective policies at the meso-level*. As in the other innovation system approaches, the research involved analysing the *structure* of innovation systems, following traditions within industrial dynamics. Throughout the 1990s, structures of systems with different delineations were explored. These included knowledge fields, e.g. biomaterials (Rickne, 2000), industries, e.g. factory automation (Carlsson and Jacobsson, 1994) and sectors, e.g. biomedical (Carlsson, 2002).This work led to version 1 of TIS.[1]

With a shift, in the end of the 1990s, from exploring static structures to analysing the dynamics of systems, it was argued that various levels of analysis interacted in transformation processes. For instance, Ehrnberg and Jacobsson (1997, p. 319) integrated four levels to explain how individual firms fare in a technological discontinuity: “We will argue that we need to understand different units of analysis: the technology, the firm, the industry, and the (regional) technological system. Moreover, these need to be integrated into a coherent whole.”

This track was continued as the empirical focus shifted to specific renewable energy technologies. Jacobsson and Johnson (2000) argued that the development of a specific TIS, e.g. centred on wind turbines, is decided in competition with both incumbent systems and other emerging systems. In that competition, there are a number of factors beyond the focal TIS that may obstruct its development: “there are … a multitude of forces which favour an ‘incumbent’ energy system, which are likely to reinforce one another in a process of cumulative causation” (ibid, p. 638).[2] As Carlsson and Jacobsson (1997, p. 303) suggested, this may reflect a strong inertia in several dimensions: “firms, institutions and networks become ‘locked in’ to ‘old’ technologies. Thus, the cumulativeness and path dependency of innovation lead to risks of lock-in into technological, institutional and networking cul-de-sacs.” There was, thus, an early appreciation of contextual factors leading to problems for TIS to emerge – an appreciation that drew on a rich and abundant literature on e.g. local search

[1] See e.g. Carlsson (1995, 1997) in which the term “technological systems” was used.
[2] Indeed, most of the listed factors leading to a new technology being repelled (ibid, table 1) were exogenous to the focal TIS.

processes (Dosi, 1988; Fransman, 1990), path dependency (David, 1985) and lock-in (Cowan, 1990; Dalum et al., 1992).[3]

Our understanding of the need to include structural elements both within the focal TIS *and in its context* contributed to the addition of a number of key sub-processes ("functions") to structural elements in the TIS framework, enabling (i) a better understanding of the dynamics of systems and (ii) drawing further lessons for policy (TIS version 2).[4] These functions (table 1) are intermediate variables between structure and system performance and by conducting a functional analysis, an analyst may be guided to the specific structural weaknesses that obstruct the dynamics of the system.

TABLE 1: *Seven sub-processes/functions in a TIS*

FUNCTIONS	… IS THE PROCESS OF STRENGTHENING:
Knowledge development and diffusion ...	the breadth and depth of the knowledge base and how that knowledge is developed, diffused and combined in the system
Entrepreneurial Experimentation ...	the testing of new technologies, applications and markets whereby new opportunities are created and a learning process is unfolded
Influence on the direction of search ...	the incentives and/or pressures for organisations to enter the technological field. These may come in the form of visions, expectations of growth potential, regulation, articulation of demand from leading customers, crises in current business, etc.
Resource mobilisation ...	the extent to which actors within the TIS is able to mobilize human and financial capital as well as complementary assets such as network infrastructure.
Market formation ...	the factors driving market formation. These include the articulation of demand from customers, institutional change, changes in price/performance. Market formation often runs through various stages, i.e. "nursing" or niche markets, e.g. in the form of demonstration projects, bridging markets and eventually mass markets.
Legitimation ...	the social acceptance and compliance with relevant institutions. Legitimacy is not given but is formed through conscious actions by organisations and individuals.
Development of positive externalities ...	the collective dimension of the innovation and diffusion process, i.e. how investments by one firm benefit other firms 'free of charge'. It also indicates the dynamics of the system since externalities magnify the strength of the other functions.

Source: Bergek et al. (2008a)

[3] Later, Jacobsson and Bergek (2011, p. 46) clarified that, from a policy perspective, "structural system weaknesses are not only found on the level of a specific TIS, but can also reside at sectoral or national system levels."

[4] Version 2.0 was first found in Johnson and Jacobsson (2001) and in more refined forms in Jacobsson and Bergek (2006), Hekkert et al. (2007), and Bergek et al. (2008a).

This development was initiated by Johnson and Jacobsson (2001, p. 91-93):

> "…industrial growth is not only influenced by factors specific to a technological system, but also by those that a range of technological system has in common....thus, our analytical framework…also need to consider elements drawn from other system approaches, in particular those which are of more general relevance within a country…Integrating different system approaches is possible since … [these] have a shared understanding of a set of basic functions that are served in an innovation system… These factors [which promote or hinder the development of these functions] may be fully technology specific, but may also influence several technological systems simultaneously. Hence, they *can be derived from a system perspective using different units of analyses: technology, industry and nation*." (our emphasis)

Hence, the strength of functions reflects structural components which are internal as well as external to a TIS - structure is, therefore, inherent in functional analysis. Take, for instance, '*resource mobilization*' which is the process by which actors mobilize human and financial capital as well as complementary assets, such as network infrastructure. In earlier phases of TIS development, these resources are necessarily brought into the TIS from the outside, e.g. through actors entering the TIS from related systems. These actors may be manufacturing firms that enter on their own or through partnership with an already established firm, actors in the capital market that fund investments or universities that adjust their educational programmes to the need of a particular TIS. Hence, analysing this function involves understanding not only the incentives for entry at the industry and sector level, but also the structural features of the capital market and the university sector at the NIS level. Also '*legitimation*' and '*influence on the direction of search'* are very strongly oriented towards the context of the TIS (as emphasised by Meelen and Farla (2013) – '*legitimation*' capturing the process of forming *social* acceptance and '*influence on the direction of search*' the process by which *new* actors are attracted to enter the TIS. In sum, TIS studies have always considered contextual systems of various kinds and structural analysis of these is a central part of functional analysis.[5]

Yet, as the framework evolved and was applied to many empirical fields, these contextual features were sometimes toned down and, perhaps, taken for granted. More importantly, the focus of research was to provide rich empirical studies that elucidate the larger process of industrial dynamics and to develop the framework as a tool to guide technology-specific

[5] This is also revealed in Negro et al.'s (2012) literature review which demonstrates that the most frequently pinpointed reasons for slow diffusion of renewables lay in the context of the focal TIS.

policies. Progress was made with respect to the framework, the methods used and our empirical understanding of the dynamics of TISs. However, although structural elements beyond the TIS were systematically analysed,[6] the conceptualization of the structural context, and its interaction with TIS dynamics, was not developed beyond that outlined above.

3. Understanding TIS contexts and interactions: some initial remarks

While it is evident that any TIS is affected by contextual structures and their developments, much previous research had no explicit conceptualizations of the context beyond that inherent in functional analysis. For example, Bergek et al. (2008a) describe how the context may affect an emerging TIS through inducement and blocking mechanisms, but do not discuss how to analyse the context in a systematic way.

Some TIS scholars have proposed frameworks that take TIS contexts more explicitly into account. Markard and Truffer (2008) combine the TIS framework with the multi-level perspective and suggest that the context can be viewed as established socio-technical regimes, complementary and competing TIS and landscape factors. This perspective is used in "context analysis"; one of three building blocks of an encompassing analysis of TIS (Markard et al., 2009). Wirth and Markard (2011) use this approach to analyse competition between first and second generation biogas technologies (and the respective innovation systems).

Another approach is to analyse TISs in their spatial contexts. For example, Binz et al. (2012, p.158) distinguish a national TIS subsystem from the international TIS that includes "globally operating actors, such as transnational companies, but also … small and medium-sized enterprises, research institutes, universities, or intermediary actors involved in technology innovation around the world." Such a perspective can be expected to become increasingly relevant as TISs mature and span different regions in the world. An example is the photovoltaic industry with strong end-user markets in e.g. Germany and Italy, major solar cell producers in China, Germany and the US and technology suppliers in e.g. Germany and Switzerland, (Dewald, 2012). In a similar vein, Wieczorek et al. (2013) show the importance of transnational linkages between nationally delineated TIS for offshore wind, where the weakness of the Dutch TIS with respect to market formation is partially offset by interactions with the UK TIS. Hence, scholars have begun to conceptualize the TIS context in different ways to accommodate for a variety of contexts.

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[6] Weaker functions are used as focussing devices for identifying structural elements that obstruct TIS dynamics.

In this paper, the context comprises the technologies,[7] institutions, actors and networks that are not part of the TIS but which have an influence on it.[8] This context is characterized by a variety of higher-order structures, each exhibiting some degree of institutional coherence in the sense of organizational fields (Wooten and Hoffmann, 2008). Examples include other technological fields, industries and the political, legal, science/educational and financial systems. Also larger sectors, such as energy supply, transportation, health-care and agriculture, exhibit institutional coherence and have been conceived of as socio-technical regimes (Geels, 2002; Rip and Kemp, 1998) that encompass a broad range of technologies, fulfilling basic functions for society. Finally, also regions and nations may exhibit varying coherences among institutional structures, as proposed by, for instance, the varieties of capitalism literature (Hall and Soskice, 2001). The degree of institutionalization of elements in these contexts may differ and influence the focal technology to a stronger or lesser degree. This may relate to established technological trajectories, professional identities, commonly held beliefs, societal discourses and shared problem agendas (Fuenfschilling and Truffer, 2014). We can, thus, think of a focal TIS as "surrounded" by a variety of contextual elements (technologies, actors, networks, institutions), some of which are aligned into more coherent contextual systems. We would argue that an enhanced TIS analysis (TIS 3.0) should identify and analyse relevant parts of these context structures and their interactions with the focal TIS.

However, clearly distinguishing a TIS from its context is challenging due to frequent structural couplings in terms of, for example, underlying knowledge bases, actors and institutions, which may "blur" the distinction between systems (Bergek et al., 2008b; Markard and Truffer, 2008).[9] At the same time, structural couplings are vital for the dynamics of individual TISs, or groups of TISs, and we emphasise these, in addition to interactions that occur when the TIS is structurally separated from its context. This is in line with literature that discusses modes of interaction between technologies (Sandén and Hillman, 2011) and socio-technical regimes (Konrad et al., 2008; Raven and Verbong, 2009).

[7] Technology is sometimes not seen as a structural component.
[8] How the focal TIS is defined is an analytical choice, which depends on the research question (Carlsson et al., 2002). Apart from the decision about whether to focus on a particular knowledge field or a particular product, the analyst must decide a level of aggregation (e.g. treat all solar cells as one TIS or different solar cell technologies as separate TISs) (Bergek et al., 2008b).
[9] Thus, we consider not only structural couplings in the technology element, and associated externalities in terms of knowledge development and diffusion (e.g. Eliasson 1997), but in all structural components.

The case of hybrid-electric and biofuel vehicles illustrates such structural couplings (cf. Nilsson et al., 2012, p. 55).The companies developing these technologies

> "… tend to operate on international markets … and between companies, significant collaborations and joint projects are carried out across the world, which means that a German or Swedish automotive manufacturer may (and do) collaborate with Japanese ones on R&D and components, and thus may be affected by Japanese R&D policies. … [T]he two fields [also] link to different adjacent sectors. The HEV system links the automotive sector to electrical propulsion systems, power electronics (i.e. semiconductors) and battery industries … The biofuels system links the automotive sector to … the agriculture and forest sectors. /.../ [A]s part of the road transport sector, [both systems] have gone through turbulent times with a global car manufacturing crisis, restructuring processes and rapidly shifting governmental policies and consumer demands. These developments take place at and across international, national and local levels."

The quote emphasizes the importance of interactions (a) between the hybrid-electric TIS and other *TIS*s (e.g. electrical/electronic components); (b) with the forestry and agricultural *sectors* for biofuels, and with the automobile *sector* for both; with institutionally coherent structures defined along (c) *geographical* and (d) *political* dimensions. In recent TIS literature, these four types of contexts have been highlighted as especially important for analysts to consider (cf. Hekkert et al., 2007; Jacobsson and Lauber, 2006; Markard and Truffer, 2008). In the following section, we will discuss these and provide examples of how they may interact with a focal TIS.

Although the rest of the paper focuses on these four main types of TIS contexts, there is an almost infinite number of context elements, the relevance of which depend on the purpose of the study. For example,

- Do we compare how TISs in different parts of the value chain complement each other (e.g. machinery development and solar cell production, electric vehicles and battery technologies)?
- Do we analyse how a TIS is affected by national and sectorial innovation systems?
- Do we study how nations or regions specialize in specific parts of the value chain and affect each other?
- Do we analyse how an emerging technology competes against an established technology?

Depending on which of these – or other – questions we pose, it makes sense to distinguish different context structures and to focus on specific relationships among the components of the TIS and the context elements (e.g. user-supplier relationships, knowledge flows etc.).[10] What kind of context model is applied depends on the research question and on how the delineation of the focal TIS.[11]

4. Interactions between a focal TIS and its contexts

4.1 Interactions between a focal TIS and other TISs[12]

A focal TIS can interact with various other TISs. Some of these interactions are competitive, i.e. two TIS compete for market shares, resources such as raw material, labour and capital, legitimacy and the attention of policy makers. Other interactions are supportive, i.e. what occurs in one TIS has a positive influence on another TIS.[13] Interactions can occur as a result of, e.g., direct rivalry/collaboration, supply chain relationships, technological complementarities and structural couplings.

4.1.1 Direct rivalry/collaboration

Much of the transitions literature has focussed on competition between emerging technological niches and incumbent sectors (regimes). This competition is distinguished from competition between emerging TISs.

Competition between emerging and mature TISs is central to the literature on technological discontinuities and Schumpeterian creative destruction, which emphasizes the advantage of the “attacker” over incumbent firms in the advent of competence-destroying or disruptive innovation (Anderson and Tushman, 1990; Christensen and Rosenbloom, 1995). Here, TIS-TIS interaction is described as purely competitive and ultimately results in the emerging TIS out-competing the incumbent. In less extreme cases, the new TIS gradually gains market share at the expense of the established TIS. In such a competitive process, the involved TISs tend to *influence each other’s direction of search*. Most notably, the incumbent TIS tends to

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[10] There is always a risk that potentially important context structures are left out of the analysis and the analyst has to assess whether to incorporate additional ones.

[11] We may also need to include sub-system relationships within TIS (e.g. the market-oriented substructure in German PV TIS as part of the overall PV-TIS (Dewald and Truffer 2011) or the role of academic R&D in TIS dynamics (Jacobsson et al., 2014).

[12] The relevant context concerning technology is not necessarily a matter of TIS-TIS interaction in the sense of that it is the full ‘other TIS’ the focal TIS is interacting with. It can be a more narrow and simple interaction, e.g. the use of new IT technologies or new power electronics components.

[13] Sandén and Hillman (2011) specified six interaction modes among technologies (and associated systems). These include modes in which two TIS compete with, or are mutually strengthened by interactions, but also asymmetric relationships, e.g. where one TIS is strengthened but not at the expense of others.

respond by strengthened *entrepreneurial experimentation*, developing new and improved products and delaying *market formation* in the new TIS. A classic example is the improvements in sailing ship technology after the introduction of steam ships (Gilfillan, 1935). A recent example is the development of ADSL modem technology as a response to the emergence of fibre optics for data transmission (De Liso and Filatrella, 2008). Incumbent TIS can also influence emerging TISs in other ways, for example by blocking the emerging TIS's *mobilization of resources*, such as labour or finance, or *delegitimize* it in the eyes of stakeholders (e.g. by spreading inaccurate information about it (Aldrich and Fiol, 1994).

Emerging TISs also compete with each other. This may take the form of *delegitimation* of rival TISs through lobbying. This was the case with biofuels in the Netherlands, where proponents of second-generation biofuels tried to decrease legitimacy of first-generation biofuels (Suurs and Hekkert, 2009; Ulmanen, 2013). However, emerging TISs that share some common concerns can benefit from collaborating to e.g. influence the institutional conditions to the benefit of all (Bergek et al., 2008b). For instance, in Germany the industry associations for small-scale hydro and wind power worked together to convince politicians that a *market formation* policy was necessary for the promotion of renewable electricity production, leading to the feed-in law in 1990 (Jacobsson and Lauber, 2006). Finally, while several TIS may compete for the same market, they may conjointly construct a market without collaboration (as in the market theory of Harrison-White (White, 2000)). For example, by having several brands of electric vehicles present in the streets, *legitimation* is strengthened for all (normality), which will be expected to strengthen also *market formation*.

4.1.2 Supply-chain interaction and technological complementarities

TISs that are part of the same supply chain may interact in several ways. First, technological interdependencies exist between different steps in the supply chain as well as within each step, i.e. the development of different components and sub-systems has to be co-ordinated. This implies that TISs related to components and sub-systems that are used in the same end-product are dependent on each other. This can cause co-ordination problems since components in complex products tend to develop at their own individual rates and can easily get out of pace with each other (Brusoni et al., 2001). For example, the development of new generation of plug-in hybrids and EVs requires innovations related to batteries and battery control systems (Berggren et al., 2009), which so far have not materialized. Hence, this interaction impacts on *knowledge development/diffusion* as well as on *entrepreneurial experimentation*.

Second, supply-chain interaction can come in the form of suppliers integrating vertically into the focal TIS, *mobilising resources* for it. For example, Bergek and Jacobsson (2003) describe how new entrants into the German wind turbine industry came from supplier industries such as gearbox and generator manufacturing. Events in these other TISs, such as market crises, provided incentives for these actors to enter the wind turbine TIS.

Hellsmark (2010) adds that the potential suppliers of capital goods may *influence the direction of search*. In the German case of gasified biomass, he situates the system builders in an industry structure with many capital goods firms and transport equipment manufacturers. The system builders (Hellsmark, 2010, pp. 324–325)

"... attract actors from the existing… industry structure by aligning the technology to their interests and existing technologies. For example, the German system builder ... FZK could draw resources from the incumbent [coal] gasification capital goods industries by offering a solution suitable for its existing reactors and downstream processes used for fossil gasification ..."

Hence, the particular design features of the biomass gasification technology were influenced by interactions with potential suppliers (and partners).

A focal TIS may also interact with complementary TISs. Individual technologies tend to be dependent on a larger infrastructure of complementary technologies (Arthur, 1988). Within such an infrastructure, developments in one TIS may influence other TISs. For example, the rapid diffusion of wind turbines and solar cells (renewables TISs) has stimulated a debate on the drawback of variable electricity sources (*delegitimation)*, inducing a demand for energy storage technologies (e.g. battery TISs) and smart grids (*market formation).* Batteries have recently become cheaper following the increased production of electric and hybrid-electric vehicles (automobile TIS), creating incentives for *entrepreneurial experiments* with battery-attached wind turbines, e.g. by General Electric (Knight, 2013) (wind turbine TIS). Moreover, increasing electricity supply from renewable energy sources (RES-E TISs) might strengthen the *legitimation* of electric vehicles (automobile TIS) since it contributes to expectations that a CO_2-neutral transport sector may be in reach. An increased use of electric vehicles (automobile TIS) could, in turn, provide storage capacity for intermittent electricity sources, such as wind and solar cells (renewables TISs) (Andersen et al., 2009).[14]

4.1.3 Structural couplings

TIS-TIS interaction can also occur as a consequence of structural couplings, i.e. when TISs 'share' components with each other. In emerging TISs, few specialised components can be expected to exist and the structural coupling with – and dependence on – other systems, is likely to be particularly important (Bergek et al., 2008b). Indeed, there are many examples of mature multi-technology industries, such as lighting, where several technologies (and their associated TISs) co-exist and interact over long periods of time (Bergek and Onufrey, 2013). For example, in lighting, multinational corporations like Philips and Siemens, are market leaders in incandescent bulbs as well as in CFLs and LEDs and market regulations, e.g. performance standards, are not technology-specific but concern general issues such as energy efficiency, quality and safety. However, there are also actors who are only active in one lighting technology, which is why it might still be relevant to analyse a LED TIS or an incandescent lamp TIS and not only a lighting TIS.

Structural couplings may result in many types of spill-overs from contextual TISs to the focal TIS. For instance, as noted above, the wind turbine industry (and RES-E in general) is now structurally coupled with the automobile industry, benefitting from reduced cost of batteries (*pecuniary external economies)*. Spill-overs may also come in the form of *knowledge diffusion* between TISs.[15] For example, Sandén and Hillman (2011) describe the knowledge spill-overs from the natural gas TIS to the biogas TIS in Sweden. Spill-overs can, however, also concern less tangible issues, such as expectations and customer preferences. In lighting, customer preferences are largely determined by the characteristics of incandescent bulbs. This resulted in an initial disappointment with the colour characteristics and appearance of new lamp technologies, such as CFL or LED, until they were re-designed to achieve a more close match with the characteristics of incandescent bulbs (Onufrey and Bergek, 2013). Thus,

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[14] In other cases, complementarities can become vulnerabilities; a stunted development of a complementary TIS can create a "reverse salient" (Hughes, 1983) that blocks the development of the focal TIS. For example, the lack of a charging infrastructure of electric and hybrid-electric plug-ins has impeded *market formation* for such vehicles.

[15] As described in the literature on diversification, companies move into new fields exactly for the purpose of achieving resource synergies of various kinds (cf., e.g., Teece et al., 1994).

institutions in the form of norms and values from the incandescent TIS influenced *legitimation*, *market formation* and, eventually, the *direction of search* of the other two TISs.

As for the regulatory aspect of institutions, it was mentioned above that the German feed-in law came into place after lobbying by advocates of hydro and wind power; that is, TIS-TIS interaction led to institutional change at the SIS level. This came to benefit investors in other renewable energy technologies (e.g. solar, biogas) as the law strengthened *market formation* broadly.

In sum, the analyst needs to grasp the direct rivalry (and collaboration) with other TIS, interactions along the value chain, with complementary TIS and through structural overlaps.

4.2 Interactions between a focal TIS and relevant sectors

Since TISs are defined in terms of a technology or a product, a central context is the sector(s) in which the focal TISs' technologies and products are applied. When the focal TIS is product-based, the most relevant sectors are often readily identifiable. In contrast, technology-based TISs (e.g. ICT or nanotechnology) are likely to span many sectors and the analyst must then choose which sectors to include in the analysis.

The sectorial context can be defined at different levels of aggregation. In some studies, the difference between a sector and a TIS is negligible. For example, automobiles and mobile phones have been analysed as sectorial innovation systems (Malerba and Nelson, 2011). Others treat sectors as broad industries, which comprise a number of different technologies and products (e.g. ICT, pharmaceuticals or agriculture) (Malerba, 2002). Yet others emphasize the societal need fulfilled by a sector, such as energy, transports or health (Geels, 2004). In this paper, we place sectors somewhere between a broad industry and a societal sector, i.e. a sector comprises all the TISs supplying products needed to serve a certain function for users, be it a broad societal function such as energy supply or food production or a more narrowly defined function, such as supply of automobiles.[16]

[16] As mentioned above, sectors are similar to TISs in terms of structural elements, but their main processes are production, distribution and use rather than innovation. Moreover, each sector relies on a set of technologies in different stages of maturity and – consequently – on different TISs to provide its function. This implies that sectors are generally much larger and more stable than individual TISs.

Within each sector, there will be interaction between the various TISs that are associated with it (i.e. TIS-TIS interaction). In this section, we are concerned with interactions between the relevant sectors and the focal TIS, where the influence may be mutual or not. To an extent, such interactions concern unidirectional influences from sector-level institutions on the functions of associated TISs:

- **Laws and regulations** are often designed for groups of technologies within a sector rather than for individual technologies. For example, the German feed-in law and the Swedish tradable green certificate system influence *market formation* for many types of renewables. The effects of such sector-level policies differ between TISs, though. For example, in the lighting sector, recent energy-efficiency regulations for lamps affect the *direction of search* within all lamp technologies, but efficiency levels have been set with the explicit purpose of stimulating *market formation* of CFLs and LED lamps at the expense of incandescent bulbs and halogen lamps.
- **Norms and values** at the sectorial level can influence individual TISs. For example, with regard to *legitimation*, public opinions about the desirability of certain technologies can be the result of dominant sectorial discourses. One example is the Swedish nuclear power trauma in the 1980s and 1990s, which reduced all energy issues to one: whether or not to phase-out Swedish nuclear power plants (Johnson and Jacobsson, 2001). As a consequence, the *legitimation* process of renewable energy technologies was weak because they were perceived as a threat to nuclear power and, thus, to the energy-intensive Swedish industries which were dependent on having a reliable supply of cheap electricity (Jacobsson and Bergek, 2004). This is yet another example of the lock-in phenomenon mentioned in section 2.
- Joint **cognitive frames** at the sectorial level can influence the *direction of search* of all TISs associated with a sector. The literature on technical change has emphasized the importance of "technological trajectories" for the rate and direction of change in individual technologies (cf. Dosi, 1982). In some cases, such trajectories range over several technologies and, thus, influence their associated TISs. One example is the lighting sector, where most development efforts since the invention of the incandescent bulb have been focused on increasing the energy efficiency of lamps (Onufrey and Bergek, 2013). This trajectory has stimulated both the emergence of new lamp technologies over time (e.g. incandescent/halogen, LFL, CFL and LED) and the

development of new and gradually improved product generations within each TIS (Onufrey, forthcoming).

- Sectors are often associated with the development of **shared political representations** such as lobbying organizations or professional associations, which are responsible for managing cognitive and regulative institutions. Partly as a consequence of such activities, sectors become objects of national economic policies aimed at correcting perceived sectorial inefficiencies. Examples include classical industrial and trade policies aiming at safeguarding employment (e.g. in the coal and shipbuilding sectors) and the recent privatization and liberalization policies in many infrastructure sectors. Such policies influence framework conditions in the sector as a whole and can influence related TIS, e.g. by opening up or closing markets for new technologies (*market formation*) or by affecting the strategies of incumbent actors in their dealing with new technologies (e.g. *influence on the direction of search*) (Lieberherr and Truffer, 2014; Markard and Truffer, 2006).

While these examples demonstrate how a sector can influence a focal TIS. TIS-sector interaction is not always unidirectional. As the example of the German 1990 feed-in law shows, TISs can influence sector-level institutions – especially when several TISs act together (Bergek et al., 2008b; Jacobsson and Lauber, 2006). Moreover, the subsequent widespread diffusion of renewable electricity technologies in Germany is now having significant effects on the electricity sector in the form of e.g. declining market share for incumbents, in electricity price fluctuations which provide challenges for the sector as a whole and by inducing some incumbents (e.g. EoN) to change strategy.

TIS-sector interactions are though not limited to one sector since many TISs are part of several sectors. For example, biomass-based transport fuels are part of the transport and automotive sectors (which uses the fuels and produces the vehicles in which they will be used respectively), but also with the agriculture and forest sectors (which produce the input materials for fuel production) and with the energy sectors (since the fuels can also be used to produce heat and electricity). Influences from these sectors do not necessarily push and pull the focal TIS in the same direction. Moreover, the importance of each sector for the focal TIS might change over time. For example, agricultural biogas was originally conceived in Germany as mostly belonging to the agricultural sector but with growing scale biogas was more aligned with the needs of the energy sector. This created negative feedback from the agricultural sector (weakening *legitimation*), which means that the biogas TIS will be subjected to influences primarily from other directions (Markard et al., 2014).

Even if the focal TIS is primarily associated with one sector, other sectors may still influence it. One example is offshore wind power, where the nuclear and fossil TISs (in the electricity sector) have been joined by actors from other sectors, e.g. shipping and fishing, as well as by the military, in efforts to weaken the process of legitimation of offshore wind power (Jacobsson and Karltorp, 2013).

Finally, interactions occur with the general sectors of finance and education which impact on *resource mobilisation*. These are of particular importance in the growth phase of a TIS as scale matters greatly then – specialised labour and large volumes of capital, at reasonable interest rates, need to be made available.

In sum, for the analyst, an understanding of the sectorial contexts and their manifold interplays with the focal TIS is needed in order to capture TIS dynamics.

4.3 Interaction between a focal TIS and the political context

As indicated above, institutional alignment is at the heart of large-scale transformation processes (Freeman and Louçã, 2002) and includes alterations in norms, beliefs and regulations (Fuenfschilling and Truffer, 2014). Since an alignment enables access to resources and markets, firms, as part of broader coalitions, compete not only in the market for goods and services but also to gain influence over institutions. As Van de Ven and Garud (1989, p. 210) put it: "firms not only compete in the market place but also in this *political institutional context*. Rival firms often cooperate to collectively manipulate the institutional context to legitimize and gain access to resources necessary for collective survival…" (our emphasis).

This involves building legitimacy, creating positive expectations and influencing the adoption of regulations shielding the market and nurturing innovations (Smith and Raven, 2012; Ulmanen, 2013). These regulations are vital for the dynamics of emerging and growing TISs in a competitive and political context strongly influenced by incumbents. The politics of sustainability transitions, therefore, implies that societal interest needs to be redefined which necessitates engagement by not only actors from emerging TIS and social movements but also political actors and major economic actors (Meadowcroft, 2011). It also implies that political ideologies may have to be influenced as these shape the understanding of acceptable solutions, including the appropriate role of government.[17]

A case demonstrating that there is no escape from politics, and the difficulties in institutional alignment, originates in the existential threat that large German utilities face with respect to the rapid deployment of various technologies supplying electricity from renewable energy sources which, as mentioned in section 4.3, encroach on the market shares of incumbents. As The Economist (2013) explains:

> "… the country's biggest utility, E.ON, has seen its share price fall by three-quarters…and its income from conventional power generation…fall by more than a third since 2010. At the second-largest utility, RWE…net income has also fallen a third since 2010. As the company's chief financial officer laments, 'conventional power generation, quite frankly, as a business unit, is fighting for its economic survival."

In response, utilities (Enel et al., 2013), and others members of a discourse coalition, are making strong attempts to delegitimize the policy framework supporting renewables at the sectorial level (EEG) and the associated technologies arguing, that it involves "over-subsidised" and "unaffordable" technologies (Lauber and Jacobsson, 2013). For instance, the intervention in early 2013 by a member of the coalition, Minister of the Environment, Peter Altmaier, proposing a cap on EEG payments, led to large political uncertainty, making investors hesitant. Ronny Meyer, managing director of offshore wind industry association WAB, informed that "the market has collapsed" (Der Spiegel, 2013) and Cuxhaven harbour, which invests substantially in infrastructure to enable deployment of offshore wind turbines, sent out a plea to the government to reduce uncertainties (Handelsblatt, 2013) which put at risk the formation of a complete and large enough supply chain. Siemens, a major supplier of capital goods to the industry, recently intervened to strengthen the process of legitimation by questioning the cost calculations put forward to justify the "unaffordability" of offshore wind power. Siemens put forward the concept of levelised social cost of energy, in contrast to levelised private costs, arguing that the former is low and not high.

As this case demonstrates, the politics of institutional alignment may influence not only *market formation* but also *legitimation*. Subsequently, if it continues to have a negative impact on *market formation*, it may lead firms in the value chain to search for business opportunities

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[17] Schenner (2011) analyses the politics behind the 'selection' of tradable green certificates in Sweden as a regulatory framework for governing investments in technologies that supply electricity from renewable energy sources.

elsewhere (*influence on the direction of search*) and to reduce *mobilisation of investment resources*. The outcome of this struggle over institutions may, therefore, have significant effects on the whole sector for electricity generation and distribution in Germany but also elsewhere as the German debate is echoed in other parts of Europe. One of many examples is the head of the Swedish parliamentary committee on Industry, Mats Odell (2014), who repeats the anti-renewables argument of the group of larger, threatened utilities (Enel et al., 2013) explicitly linking the price of electricity (for non-privileged customers) of about 28 eurocents to wind power policy.[18] Yet, a simple calculation reveals that the impact is insignificant.[19]

In sum, analysts needs to understand the politics of institutional change and how it influences functional dynamics, e.g. via the discourses of various coalitions.

4.4 TIS development in geographical contexts

The technological, sectorial and political dimensions of the context typically overlap in specific geographical areas, which create distinct contexts on their own. The NIS and later the RIS approach chose geographical territories as seemingly obvious system boundaries for identifying interactions among firms, educational structures and labour markets. In a nutshell, geographical areas, be it nation states, regions, cities, or associations of states (like the EU) can be seen as the historical result of organizational and institutional alignment processes (involving industrial sectors, cultural norms, formal regulations, educational systems, labour markets, political systems, etc.) and natural context conditions. These territories are typically ruled by governmental bodies, which ascertain that formal regulations are respected. Also, they define the jurisdictional territories in which political processes play out. Empirically, we can observe a high geographical variety of these socio-spatial configurations, which may foster or hinder specific forms of innovation that are crucial for the formation and maturation of new TIS. An obvious point relates to technology and innovation policy which are most often determined at a national or regional level. It was, therefore, only a small step for NIS

[18] Another example is the European Commission's (2013, p. 2) Green Paper which discusses climate and energy policy for 2030 where it is argued that a central consideration for future policies is "concerns of households about the affordability of energy and of businesses with respect to competitiveness".

[19] In 2012, wind power supply was 51 TWh and was remunerated by 8.8 eurocents/kWh. The spot price for electricity was 5.4 eurocents/kWh. The extra cost for wind power would then be 3.4 eurocents/kWh times 51 TWh, which equals roughly 1.7 billion Euro. Total electricity consumption was 607 TWh. If we divide the extra cost over this consumption, the added cost is 0.29 eurocent/kWh.

and RIS scholars to analyse the effectiveness of specific socio-spatial arrangements with regard to the development of new technologies, industries and/or consumer patterns (Sharif, 2006). Evidence suggest that while there are strong globalizing tendencies, regional diversity has remained high (Morgan, 2004; Storper, 1997). Geographical contexts, therefore, continue to play an important role when analysing TIS.

The TIS concept was developed starting with a critique of territorial innovation system approaches for its unreflecting definition of system boundaries (Carlsson and Stankiewicz, 1991; see also Oinas and Malecki, 2002). However, most empirical applications remained restricted to the national scale (Coenen et al., 2012) while some endeavoured comparative analyses of two or more nationally delimited TIS (Bergek and Jacobsson, 2003; Lovio and Kivimaa, 2012; McDowall et al., 2013; Negro et al., 2007; Vasseur et al., 2013). Little attention was paid to structural couplings with sub-or supra-national contexts. Carlsson (2006) even diagnosed that innovation systems research largely ignored the growing globalization of innovative activities and he urged for explicitly adopting an international view on innovation processes. However, so far, only a limited number of approaches have taken up the challenge to develop such a framework.

A recent recall for bringing geography back into transition studies in general, and TIS in particular, was formulated by Truffer and Coenen (2012). They identified two[20] major integrative realms: i) socio-spatial embedding, and ii) multi-scalarity.

The first realm where geographical contexts have to be considered more attentively relates to the embedding of TIS (or parts of TIS) into specific regional, national or supranational territorial contexts. The question is essentially about the “Wheres” of successful TIS formation. Previous TIS studies have to some extent dealt with questions such as in how far system formation processes depend on “external factors” related to broader institutional and organizational context conditions such as national educational systems, regional labour markets, specific regulations, etc. and how institutional and organizational configurations in different places can be evaluated with regard to their suitability to drive further system maturation. However, not much emphasis was put on interdependencies that exist between these different dimensions in particular geographical contexts, hampering the potential for transferring lessons from one application context to another.

[20] The third dimension of “power” has very strong overlap with the political context, addressed in section 4.3.

A closer look into local embedding processes promises to open up a number of new perspectives on TIS formation. It may enable the identification of the set of conditions for innovation success that seem to exist in specific places but not in others, or it may highlight potential synergies between technology, environment and regional policies, or it may allow for specifying the potential contribution of local and regional initiatives to the promotion of sustainability transitions. An example is the early market formation processes for PV in Germany which relied on the system building efforts of a particular kind of citizen groups (solar civic associations) that were active in a number of local communities across Germany (Dewald and Truffer 2012). These initiatives did not only educate early adopters of PV panels, but also had to integrate the different components into working PV systems as well as organize the instalment, maintenance and servicing of these installations. For this they needed to draw in local traders and plumbers. Furthermore, they lobbied for support measures in their local political contexts. In sum, these actor groups were able to leverage the specific local institutional structures for building a functioning market at the local scale (i.e. including the supply, the demand and the regulatory contexts). This local "proof of feasibility", was absolutely crucial for legitimizing the introduction of a national feed-in tariff, later on. This specific way of supporting *market formation* also had a strong impact on other TIS functions and by this supported overall TIS development in Germany (Dewald and Truffer 2011). Socio-spatial embedding obviously plays an even more important role when analysing TIS development in emerging economies and developing countries. If anything, geographical variety of institutional and organizational structures is even larger in these places. Transporting TIS studies to the Global South might, however, not only require heightened attention for spatial embedding but may also inspire the formulation of some conceptual innovations in TIS research (see, e.g., Jacobsson and Bergek, 2006; Murphy, 2013).

The second core issue that emerges when coupling TIS with spatial contexts relates to scale: research on territorial innovation systems has repeatedly been criticized in economic geography for being far too inward-looking with regard to identifying regional success conditions for technology development. It was observed that not all relevant processes happen in one specific region or nation (Asheim and Isaksen, 2002; Bunnell and Coe, 2001; Maskell et al., 2006), as already voiced by Carlsson and Stankiewicz (1991). Even in the definition of a specific "region" it is often hard to decide whether actors, networks and institutions are actually located there. Multinational firms, for instance, may be active in a specific region, but they are also connected to many other places in the world. Their corporate strategies will depend on an integrated view of their whole company and not only on the interests of a single plant. In order to understand conditions for successful regional development, geographers have, therefore, repeated that it is important to take scale into account, i.e. the potentially global networks that are constituted by different dimensions of proximity, besides geographical also cultural, organizational and cognitive (Boschma, 2005).

An explicit inclusion of scale enables addressing questions which were hitherto rarely dealt with in the literature. In line with companies establishing more and more global value chains, also innovation activity has seen a tendency of being organized on a global scale (Carlsson 2006). This does, however, not negate the importance of specific conditions for innovation success that are anchored in national or regional systems. Issues related to tacit knowledge or the existence of specific local conditions for carrying out research, development or market introduction may continue to be crucial for innovation success. As a consequence, we see an increasingly intricate geographical pattern of innovation activities that may consist of hotspots of innovation activity, interconnected over large distances. In particular, *knowledge development*, *entrepreneurial experimentation* and *market formation* may exhibit very different geographies, being anchored in different parts of the world, while interconnecting through globally spanning actors, networks or institutions (Binz et al. 2013; Oinas and Malecki 2002). Analysts, therefore, have to increasingly reflect on how they set the geographical boundaries of their TIS analysis. Even though a truly global analysis is often not possible due to data availability and the required effort for data gathering, one should question whether the majority of relevant TIS elements and functions will be detectable in any given territory.

5. Conclusions and lessons for analysts

In TIS studies, the structural context of the system has always been taken into account but when functional analysis is used as a focusing device for finding system weaknesses, only those contextual factors that actually impact on the focal TIS are made visible. Even though this simplifies the representation of the context, and its interaction with the TIS, it risks leading to an under-conceptualization of TIS contexts and to a neglect of contextual factors. This inspired several authors to criticize the approach and, sometimes, propose improvements. The purpose of this paper was to (i) make the knowledge underlying the TIS framework more explicit and (ii) take a few steps towards making it more complete in its conceptualisation of interactions between a TIS and its contexts (TIS v. 3).

We explained where the framework came from and that the nature of the processes that functional analysis captures involves crossing system boundaries, incorporating structural factors at different system levels. We proceeded with improving the conceptualisation of TIS-context interactions by elaborating on four contextual dimensions. Although the discussion is non-exhaustive, it is plain that there may be many and significant interactions between a focal TIS and its contexts. Instead of an inward-looking framework, the TIS approach has, therefore, much in common with Myrdal's (1957, p. 18) perspective on dynamics as interplay between internal and external sources of change:

"…the main scientific task is to analyse the causal inter-relations within the system itself as it moves under the influence of outside pushes and pulls and the momentum of its own internal processes."

The richer conceptualization is helpful since it further facilitates finding the origins of systemic problems, some of which may be overcome by technology-specific policies while others require different instruments.

For analysts engaged in understanding the formation and growth of a TIS, a thorough understanding of the TIS is question has to be supplemented with insights into a broad contextual dynamics and its interactions with the TIS. The first and main lesson for analysts is, therefore, the diversity of issues that need to be included; from politics to technological couplings with other TIS, within and beyond sectorial boundaries. The analyst needs, consequently, to acquire a multi-disciplinary understanding of industrial dynamics, including a more than superficial grasp of the technologies involved.

Second, the analyst has to map interactions with other TIS - both incumbent and emerging - through e.g. direct rivalry/collaboration; supply-chain relationships, technological complementarities and structural couplings. Analysts may have to identify actors outside the focal TIS that are in the forefront of developing knowledge needed as well as causes of technical bottlenecks that reside outside the focal TIS (e.g. in a supplier TIS). They may also need to analyse the incentives for entry from related TISs as well as the influence of internal struggles over resources and legitimacy within actors who are present in several TISs. They may need to grasp the interactions with complementary TIS, e.g. infrastructure. As the value chain is often long, the focal TIS may interact with many other TIS through structural overlaps. The focal TIS may benefit from functional dynamics of other TIS which impact on institutional change (regulatory, cognitive and normative) at the sectorial level. It may also benefit from the knowledge base and products (structural element of technology), generated in other TIS, e.g. batteries. However, it may also face competition for scarce resources, such as land, biomass and skilled labour. The analysts, therefore, need to grasp the significance of overlaps for the interlinked dynamics of two or more TIS.

Third, there is mutual interaction between TIS and one or more sectors which the analyst needs to grasp. Interaction may take place due to e.g. sector-specific regulations, norms and cognitive frames. Such an analysis may include issues such as: to what extent is path dependency at the sector level an obstacle or an enabler for the development of specific TISs (cf. Onufrey, forthcoming) and what are the sources of path-dependency in individual sectors? What role do incumbent actors who are not part of the focal TIS play in its development? Moreover, as *resource mobilisation* involves engaging actors in the context, the analyst needs to understand the conditions under which this may take place, e.g. how the broader capital market and higher educational system work.

Fourth, an analyst needs to understand the politics of institutional change, e.g. via the discourses of various coalitions. Analysing the process of *legitimation* requires ascertaining how TIS actors organise their advocacy and how it relates to the advocacy of actors in the context of the TIS. An analyst also needs to be aware of the risk of being manipulated by statements from various advocates, including media and politicians, especially concerning TISs which are highly contested.

Fifth, analysts should tread warily when setting the territorial boundaries within which they want to analyse a specific TIS. Ideally, they would first identify the global set of TIS-elements and functions and then determine whether their preferred spatial delimitation (e.g. the focus on a specific country) represents a sufficiently interconnected sub-system in the global TIS (e.g. as presented in Binz et al. 2013). Furthermore, an analyst should carefully identify which sort of “external factors” have to be taken into account and whether these are sufficiently independent of each other to be treated as isolated forces. If not, the system boundary would have to be redefined in order to allow for more complex system topologies. For instance, the analysis would consist of a set of nested TIS structures if a national TIS is heavily influenced by higher-order policies (e.g. as in the case of a national offshore wind TIS being part of a European TIS, see Wieczorek et al 2013). Another case could be that the analysis should be framed as the coupled dynamics of two national TIS (such as in the case of PV TIS development in Germany and China, see Quitzow 2013).

Finally, the many possible types of interactions mean that the focal TIS may impact on the structural context. This goes much beyond market formation which encroaches on the incumbents' market shares and includes shaping institutional alignment and generating other positive externalities for TISs that emerge in parallel. It also includes influencing incumbents to search in new directions. For instance, large German utilities now argue for special subsidies to very large-scale solar installations after having lobbied against the EEG and solar cells for decades. By making the context explicit and conceptually improved, the building blocks are, therefore, also in place to study socio-technical transitions that go beyond the growth of an individual TIS. We may, thus, begin a discussion of how different (interrelated) TIS add up over time to sectorial transformations on a local, national and international scale and, thereby, provide a conceptual account of sustainability transitions building on a TIS perspective.

6. References

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