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Technological innovation systems and the multi-level perspective: Towards an integrated framework

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Abstract

Technological innovation systems and the multi-level framework are closely related concepts for the study of far-reaching technological change. They draw on common theoretical roots and analyze similar empirical phenomena. However, they have developed rather independent research strands over the past few years. The paper reviews the state of the art of both concepts and explores commonalities as well as differences. Against this background, we outline first elements of a path towards an integrated framework that combines the strengths of the two approaches and allows providing a better understanding of radical innovation processes and socio-technical transformations.

Keywords: Innovation systems; Multi-level framework; Radical innovation; Technological change

1. Introduction

The analysis of radical innovation processes and fundamental transformations of entire economic sectors is one of the classical research fields in the innovation literature. An improved understanding of these processes is important, but demanding. It is important because of the consequences they have for suppliers, producers and customers in a particular field as well as for policy makers and society as a whole. And it is demanding because the underlying innovation processes are complex as they typically depend on the co-development of new socio-technical configurations, new market structures, new actors and new institutional settings. Furthermore, innovation and larger transition processes tend to depend on spatial and historical context conditions, which pose a formidable challenge to theory building and research methodologies that aim at generalized empirical findings.

Innovation scholars have approached the analysis of such fundamental transformation processes from at least two different perspectives. Either the focus is on the prospects and dynamics of a particular innovation (e.g. fuel cell technology) that has a potential to contribute to far reaching changes. Such an 'emerging technology perspective' is typically concerned with the most important drivers and barriers for a successful diffusion of a particular technology or product. Theory building will then focus on the identification of general patterns shared by different innovation processes. An alternative approach would be to investigate broader transition processes at a more aggregated level (e.g. electricity supply in general), involving a variety of innovations, which

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possibly lead to a substitution of established technologies and a transformation of sectoral structures. In this 'transition perspective', a guiding question is which factors drive these transformation processes. Generalization may be deduced from comparing different transformations.

Both perspectives, in fact, contribute to a deeper understanding of radical innovation and transformation processes and would ideally lead to similar conclusions. Both approaches may also complement each other. In the innovation literature, two major strands of conceptual and empirical work have emerged that address the two perspectives: innovation system approaches and the literature on technological transitions.

The concept of innovation systems has been defined at different levels for different purposes of analysis (Carlsson et al., 2002; Carlsson, 2006; Chang and Chen, 2004; Edquist, 1997). In the following, we will concentrate on its role for the analysis of radical innovation processes. Innovation systems are composed of networks of actors and institutions that develop, diffuse and use innovations (e.g. Carlsson and Stankiewicz, 1995; Edquist, 2005; Malerba, 2002). Different innovation systems can be assessed and compared with regard to the functions they fulfill (Bergek et al., 2005; Hekkert et al., 2007; Johnson, 2001; Negro et al., 2007). Functions are emergent properties of the interplay between actors and institutions. They can be assessed in order to derive policy recommendations, e.g. for supporting the development of a specific technology (*ibid.*). Furthermore, the systems perspective has proven its virtue for the explanation of innovation dynamics at different levels of aggregation (e.g. Bergek and Jacobsson, 2003; Jacobsson and Bergek, 2004).

The literature on technological transitions, a second stream that has gained considerable attention in recent years, has elaborated the concepts of socio-technical regimes, niches and landscapes, which form the basis of a so-called multi-level framework to study the transformation of regimes (e.g. Elzen et al., 2004; Geels, 2002; Raven, 2007; Rip and Kemp, 1998; Smith et al., 2004; van den Ende and Kemp, 1999). The multi-level framework conceives technological transitions as interactive processes of change at the micro-level of niches and the meso-level of socio-technical regimes both embedded in a broader landscape of factors at the macro-level (e.g. Geels, 2002, 2005b; Verbong and Geels, 2007). The technological transitions framework has inspired recommendations for policy intervention and broader governance issues by elaborating concepts such as strategic niche management (Hoogma et al., 2002; Kemp et al., 1998; Smith, 2003; Truffer et al., 2003) or transition management (Kemp and Loorbach, 2006; Kemp and Rotmans, 2005).

Both strands have emerged largely independent of each other although they aim at explaining similar empirical phenomena and are based on common conceptual grounds. Both highlight the importance of networks and learning processes together with the crucial role of institutions for successful innovation processes. Both acknowledge phenomena such as path dependency, lock-in, interdependence, non-linearity and coupled dynamics. More generally, both concepts are rooted in evolutionary economic theorizing. While one may argue that system theory in sociology or natural sciences is quite different from evolutionary theory (cf. Malerba, 2002, p. 249), this does not apply for the innovation systems framework. Instead, innovation system scholars explicitly refer to evolutionary theory (e.g. Carlsson and Stankiewicz, 1991; Chaminade and Edquist, 2005; Edquist, 1997; Malerba, 2002).

A further commonality of the systems approach and the multi-level framework is that scholars in both fields usually apply an interdisciplinary perspective and account for the particularities of spatial and historical contexts. Finally, both frameworks can look back on several years of theoretical development and a large number of empirical case studies, in which they have been tested and refined. Both have also been developed towards informing innovation policy making.

Due to these commonalities the question arises how the two frameworks relate to each other and whether parallels or complementarities can be exploited. Moreover, there are indications that the distance between the two approaches is decreasing. While they used to represent two largely separated perspectives, scholars have for example started to apply the multi-level framework also to the study of emerging technologies (e.g. Geels and Raven, 2006; Raven and Geels, 2006). Therefore the question arises whether the multi-level concept provides insights that the innovation systems approach neglects and vice versa.

In this paper, we explore the conceptual commonalities of the innovation systems approach and the multi-level framework when applied to far reaching innovation and transformation processes. We particularly address their respective strengths and shortcomings with regard to the definition and empirical delineation of the core concepts. On this basis, we finally propose the concept of *technological innovation systems* that allows integrating the multi-level framework and the innovation system concept for the study of emerging, far-reaching novelties. This might constitute a promising starting point for the proponents of the two strands to reflect and use the merits the approach they have not applied so far.

The text is structured as follows. In Sections 2 and 3 we review the two bodies of literature with regard to their basic terms and concepts. In particular, we will work out the diversity of interpretations of the key terms and discuss the issue of how to delineate and apply these concepts empirically. Section 4 addresses commonalities and differences between the key terms (systems, regimes, niches) of both frameworks in terms of conceptual composition, level of aggregation and their role for innovation processes. Furthermore, we discuss shortcomings of each approach in order to identify the room for synergy and complementarity. Section 5 outlines a path of research towards an integrated framework and defines 'technological innovation systems' (TIS) in a narrower way than existing system concepts. We also specify a preliminary set of minimum criteria an empirical field has to fulfill so that the application of the TIS concept makes sense. These steps allow bridging the gap between the two approaches and arriving at a mutual translation of insights. Section 6 concludes with a reflection of our results and propositions.

2. Innovation system approaches for technology specific analyses

Innovation systems have been defined at different levels for different purposes of analysis. National systems of innovation was the first concept elaborated in the literature. Rooted in evolutionary economic theorizing on socio-technical change it was introduced and elaborated, among others, by Lundvall (1992), Freeman (1997) and Nelson (1993). Later on, regional systems of innovation, sectoral systems of innovation and production as well as technological systems were proposed on the same theoretical basis as complementary perspectives (see Carlsson et al., 2002; Carlsson, 2007; Chang and Chen, 2004 or Edquist, 1997 for an overview). While the national focus dominates the innovation systems literature of the past 20 years with a share of about 50% of all publications, regional innovation systems cover 25%, technological systems 19% and sectoral systems 6% (Carlsson, 2007). In a broader sense, the concept of large technical systems (LTS) may as well be regarded as a family member of innovation system approaches (cf. Geels, 2004, 897) although innovation processes and evolutionary thinking have not played a dominant role in the LTS literature.

Due to our interest in radical innovation processes, we will in the following section concentrate on those system concepts that have been developed for a technology specific perspective on innovation processes. Our analytical focus is the technological systems concept (e.g. Carlsson and Stankiewicz, 1995), which we compare and contrast with a general conceptualization of innovation systems (Edquist, 2005) and sectoral systems of innovation and production (Malerba, 2002). The relationship between territorial system of innovation concepts and the multi-level approach has been elaborated elsewhere (Truffer, in press).

A system in general is an entity comprising elements that interact with one another. It is a model of reality designed for analytical purpose. This implies a clear distinction between the system and its environment. Systems are characterized by their structure including system borders, the number and type of system elements, their interrelations and the relations between the system and its environment. Innovation systems, more specifically, can be conceptualized as a set of organizations and institutions and the relationships among them (Edquist, 2005).[1] Organizations (also actors or agents) typically encompass private firms or firm sub-units, governmental and non-governmental agencies, universities, research facilities, venture capitalists, associations, etc. Institutions, on the other hand, can be regarded as the rules of the game (*ibid.*) comprising laws and regulations, socio-cultural as well as technical norms, use patterns, shared expectations, etc.[2]

The relationships among the system components, i.e. among actors, among institutions but also between actors and institutions, are manifold. Actors may compete but also collaborate (or network) with each other or they may perform transactions, i.e. trade goods, services or knowledge. Institutions may support each other but they may also be in conflict (Edquist, 2005). Moreover, there may be a certain hierarchy in the institutional set up. Institutions set incentives for actors to perform certain activities and to avoid others. The key metaphor here is that actors are embedded in an institutional context. Actors, however, may also deliberately change or adapt existing institutions or create new ones, which means that there is a dual subject–object relationship between actors and institutions ('mutual embeddedness', cf. Edquist and Johnson, 1997).

[1] This general concept is in line with recent articles on the technological systems approach (e.g. Hekkert et al., 2007; Jacobsson and Bergek, 2004; Jacobsson and Johnson, 2000). It is different, however, from the SSI concept, for which - apart from agents and institutions - products, technologies and different kinds of processes/interactions as basic elements have been suggested (Malerba, 2002).

[2] Note that this rather narrow interpretation of institutions is not shared by all scholars in the field (cf. Carlsson, 2007).

2.1. Basic concept

Innovation systems[3] that are assigned to a specific technology or product have been referred to as *technological systems* (TS) in the literature. Many studies cite Carlsson and Stankiewicz (1991) who defined a technological system as a

> "network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion and utilization of technology" (Carlsson and Stankiewicz, 1991, p. 111).

This definition does not make a clear distinction between new and established technologies, which becomes relevant if the analysis is concerned with innovations that are radically different from established technologies (see below). Whereas 'generation' certainly refers to *new* technologies, 'diffusion and utilization' may also include *established* technologies. Strictly speaking, Carlsson and Stankiewicz (1995) conceptualize a technological system as an entity that creates novelties and supports established technologies at the same time. While the distinction may be less important for incremental innovations, we think that the issue becomes crucial if radical innovations are in the focus of analysis. The sectoral systems of innovation and production (SSI) approach makes an interesting contribution in this respect because it explicitly distinguishes new and established products in its definition and highlights that

> ". . . because the notion of sectoral systems includes innovation and production with the related demand and market processes, for analytical purposes one could examine separately a sectoral innovation system, a sectoral production system and a sectoral distribution-market system" (Malerba, 2002, 251).

We may therefore interpret both the TS and the SSI concept in a way that they include an *innovation part* that creates, diffuses and uses new products (or technologies) and a *production part*, which is 'responsible' for the established products (or technologies). The latter encompasses the creation of incremental innovations, i.e. the continuous improvement of the production processes and established product lines in a given system or sector. It is the part that slowly evolves along a technological trajectory as long as no fundamental challenges arise at the outside. The innovation part of the system, on the other hand, may bring about radical innovations, which lead to a significant transformation of the established production part or even to the emergence of an entirely new production system. In such situations, we also expect that actors, networks and institutions involved in radical innovation processes are not identical with those performing activities that sustain an established system, although there might well be an overlap (e.g. at the level of a firm, which includes different business units). Therefore, a more clear-cut identification of the innovation part of systems may be necessary. Such an approach would be in line with the conceptualization of systems of innovation (SI) by Edquist (2005), which concentrates on the innovation part.

> "An SI has a function, i.e. it is performing or achieving something. The main function in SIs is to pursue innovation processes, i.e. to develop, diffuse and use innovations." (Edquist, 2005; 182).

Another challenge with regard to the basic concept is related to the question whether the innovation itself, e.g. a technology or product, should be part of the innovation system or not. Some approaches such as SSI and LTS regard technologies or products as integral parts of the system (Hughes, 1987; Malerba, 2002). In contrast, the technological systems concept and the innovation systems approach as defined by Edquist (2005) do not. Instead, they imply that innovation in general, or new technology in particular, is the output of the system. Edquist (2004) regards this analytical cut as a distinction between the determinants and the result of the innovation process.

> ". . . I believe it is useful to draw clear distinctions between independent and dependent variables . . . this means that it is important to draw distinctions among the determinants of innovation, the propensity to innovate (or innovations as such), and the consequences of innovations." (Edquist, 2004; 487).

We think that such a distinction has to be seen as an analytical choice. In reality, the results of the innovation process feed back directly into its determinants. Due to this close and critical interaction we suggest to regard the innovation itself as a part of the system, a part that is not genuinely different from other system elements except from the fact that it is the element an innovation researcher

[3] We will use the notion 'innovation system' as a generic term for all system concepts discussed in this paper. The same notion, however, is also used to refer the concept of Edquist (2005). We tried to make this difference clear in the respective parts of the text.

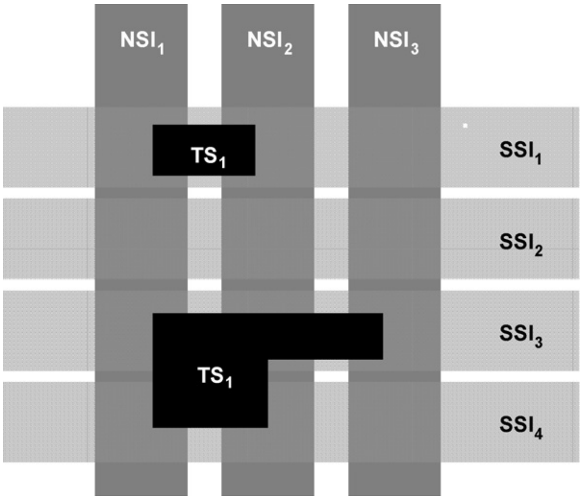

Fig. 1. Potential relationship between national (NSI) and sectoral (SSI) systems of innovation and a technological system (TS).

might be most interested in studying, cf. Section 5.

2.2. System delineation

The issue of how to delineate an innovation system, i.e. to discriminate between the system and its environment, is crucial and challenging (Carlsson et al., 2002; Edquist, 2005). It is crucial because delineation is likely to affect the findings and it is challenging because there is no right or wrong way to draw system boundaries, given the fact that the system is a theoretical construct applied to and defined in a specific research context.

System delineation, firstly, depends on the chosen system concept. National or regional systems of innovation, for example, are primarily delineated on a spatial basis assuming that they are largely determined by organizations and institutions inherently characterized by a certain territorial sphere of influence and interaction (Moulaert and Sekia, 2003). Sectoral systems, in contrast, may be determined in terms of industry structures that usually cross geographic boundaries, cf. Fig. 1. Technological systems typically cross geographic as well as sectoral boundaries (Hekkert et al., 2007). Here delineation has to consider the structure of a specific technology in the sense of a knowledge field, or a product or market respectively (cf. Carlsson et al., 2002). System delineation still remains challenging because different technologies or knowledge fields are empirically intertwined and we are often facing rather a technology continuum than separate fields (ibid.).

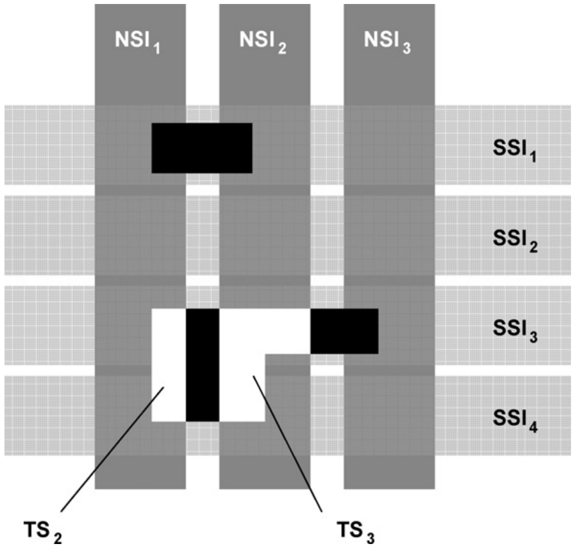

Fig. 2. Example of a delineation of two 'sub'-TS in spatial and sectoral terms.

In the case of fuel cell technology[4], for example, we may ask whether to concentrate the analysis just on the core energy conversion device (the stack) and the specific catalyst technology or whether to also include auxiliary technologies for cooling, power control, power conversion, heat exchange, etc. Shall we limit the study to one catalyst technology or include all available ones and the corresponding fuel cell types? Or shall we rather concentrate on fuel cell technologies for a specific application field, e.g. mobile, stationary or portable fuel cells?

These questions are examples for the general choice between analytical breadth or depth and whether to include some or all applications in a selected technological field (Bergek et al., 2005). A general answer of how to deal with such choices is that system delineation depends to a large extent on the research question and the purpose of analysis *(descriptive delineation)*. Even more, system delineation can be perceived as a process with a starting point and adjustments to system boundaries as the understanding of the system increases (*ibid.*). Whatever boundary is chosen with regard to technology, system delineation in these cases usually also encompasses a further specification in spatial terms (*ibid.*). In Fig. 2, for example, two technological systems, which could also be conceptualized as parts of a larger one (TS_1, cf. Fig. 1), were delineated on a spatial and sectoral basis resulting in TS_2 and TS_3. Consider, again,

[4] For a detailed description of fuel cells see e.g. Carrette et al. (2001) with regard to technological characteristics and Markard and Truffer (in press) with regard to innovation characteristics.

fuel cell technology that can be used for mobile, stationary and portable applications. While TS_1 represents the technological system of fuel cells as a whole, TS_2 could be the system on stationary and portable fuel cells in the US and TS_3 the one in Japan. Such a set up can be used to compare the performance of technological systems in different countries.

In contrast or rather as a complement, innovation scholars have suggested the use of technology distance indicators or bibliometric and patent analyses in order to delineate innovation systems on an empirical basis (Carlsson et al., 2002). The question in how far national characteristics of innovation systems are still important or whether they diminish due to an increasing internationalization (Carlsson, 2006), for example, is an expression of this approach to system delineation. It is based on the assumption that system boundaries are 'somehow out there', i.e. that a system has certain characteristics, which may be empirically identified in a specific innovation field (*conceptual delineation*). This corresponds to the suggestion to define system boundaries in a way that variables assigned to the environment are *relatively* independent of the behavior of the system (Matthies, 2002). In other words, in the conceptual delineation approach system boundaries are determined in a way that the interactions among components within the system are more intense than the interactions between the system and its environment.

A third proposition to define system boundaries has been made by Edquist (2005) on the basis of activities that are conceptualized as the key determinants of the innovation process. The system is said to encompass all important factors[5] that influence the development, diffusion and use of innovations (Edquist, 2005). Similarly, it has been suggested that system delineation can be made operational by identifying the mechanisms that promote or hinder the development of system functions (Johnson and Jacobsson, 2001).

These latter propositions of Edquist (2005) and Johnson and Jacobsson (2001), in our view, are thorny for several reasons. First, including 'all important factors' means that no distinction is made between those influences, which are closely related to the innovation process and part of potential feedback loops, and those that are not affected by the innovation process. Influences such as prices of inputs (energy, labor, material, capital, etc.), economic growth or demographic change are certainly important for a broad series of innovation systems although hardly affected by the outcome of a particular system. In the terminology of systems theory, such factors are (external) *parameters*. Secondly, this particular delineation approach poses problems when it comes to a comparison of systems. Whenever two systems influence each other, which is likely, they cannot be treated and analyzed separately any more. Thirdly, influential factors also include those that *hinder or block* the innovation process. To conceptualize such barriers or opposing actors, for example, as elements of the innovation system is inconsistent with system definitions formulated in a way that system components *contribute* to the generation, diffusion and use of innovations (see above).

2.3. Analysis of innovation systems in terms of functions or activities

In recent years, the identification and assessment of functions, or activities, of innovation systems has received a lot of attention. This 'functional perspective' on innovation systems emphasizes the importance of what the system does or how it works in comparison to how it is composed or structured (Bergek et al., 2005). Still, structure and function are two intertwined sides of the same object, the system. System structure influences its function and vice versa. But this relationship is ambiguous, which means that systems, which are structurally different, may be similar in terms of functions and the other way round. As a consequence, there is no optimal structure to assure a well performing system (cf. Edquist, 2005; Malerba, 2002). Still, a system can be said to perform better or worse than another one. And the key to a performance comparison of innovation systems is their assessment in terms of functions. On the basis of system comparisons scholars are finally able to arrive at policy recommendations with the goal to improve system performance or to eliminate structures that block system functions, respectively (cf. Section 2.4; Bergek et al., 2005; Edquist, 2004).

Whereas the overall system function can be conceptualized as the generation, diffusion and use of innovation (cf. Edquist, 2005), various *sub-functions*[6] have been assigned to innovation systems including for example the generation and diffusion of knowledge, the guidance of search processes or the creation of markets. The quality of a sub-function depends on the activities or effects of

[5] Note that the author uses the notion of factors largely as a synonym for system components (organizations, institutions).

[6] We use the notion of sub-functions in the following to draw a distinction to the overall system function. In most of the literature cited this distinction is less explicit and authors also use the word functions at the sub-system level.

Table 1
Proposed sub-functions – or activities – of innovation systems

Hekkert et al. (2007)	Bergek et al. (2005)	Chaminade and Edquist (2005)
Entrepreneurial activities	Entrepreneurial experimentation	Creating and changing organizations
Knowledge development Knowledge diffusion	Knowledge development and diffusion	Provision of R&D Provision of education and training
Guidance of the search Market formation	Influence on the direction of search Market formation	Articulation of quality requirements from the demand side Formation of new product markets
Resources mobilization	Resource mobilization	Incubating activities Financing of innovation processes Provision of consultancy services
Creation of legitimacy	Legitimation Development of positive externalities	Creation/change of institutions Networking and interactive learning

a certain set of (or even all) system components and their relationships. The quality of the overall system function depends on the quality and the interaction of the sub-functions. As the sub-functions are not independent of one another it is ambiguous of how they add up to the overall system function.

A series of empirical as well as conceptual articles have proposed different sets of sub-functions for the analysis of innovation systems (see Bergek et al. (2005) or Hekkert et al. (2007) for an overview). Similar to the notion of functions, other authors have proposed to analyze innovation systems in terms of activities (Chaminade and Edquist, 2005; Edquist, 2005; Liu and White, 2001). Activities are conceptualized as "the factors that influence the development, diffusion, and use of innovations" (Edquist, 2005, 182). For a comparison of different propositions of sub-functions or activities see Table 1.

In order to make the results of different innovation case studies comparable, it remains a crucial issue for conceptual improvement to arrive at a set of functions that is commonly defined and understood. As a criterion to determine, for example, whether a chosen set of functions is encompassing enough, Hekkert et al. (2007) have proposed that every innovation event in the course of development of an innovation system should be attributable to at least one sub-function. While both approaches, functions and activities, aim in the same direction, the notion of functions may eventually turn out to provide a better fit with the systems concept. Functions can well be ascribed to all types of system elements, i.e. to actors, institutions and networks. Activities, however, in a narrow interpretation of the notion, can only be performed by actors not by institutions or networks. Institutions in the sense of rule sets are passive and therefore they cannot carry out activities directly (cf. Edquist, 2005). Instead, they set incentives for actors to perform activities. Networks, in a similar vein, facilitate the execution of activities. Moreover, the notion of activities is still closely linked to the micro-level of discrete actors or organizations, i.e. one might be inclined to perceive 'system level activity' as the sum of micro-level activities. Functions, on the other hand, are rather associated with a holistic, systemic view, which means that a system function embodies more than the sum of the activities and effects of each of the system's elements.

2.4. Assessing system performance

So far, system performance assessments have been carried out at the system and the sub-system level. A commonly used indicator for the overall performance of a technological system is the diffusion of the innovative technology or product under study (e.g. Bergek and Jacobsson, 2003; Jacobsson et al., 2004; Jacobsson and Bergek, 2004). In most cases, however, innovation diffusion was rather used implicitly as the main indicator for system performance. Carlsson et al. (2002) addressed the challenges of system performance assessment explicitly and systematically. The authors propose a differentiation according to (i) the level of analysis, i.e. whether a technology or a product is in the focus and (ii) the maturity of the system.

If a technology or knowledge field is in the focus, generation and diffusion of knowledge is said to be the core function along which to measure performance (*ibid.*). While patents or bibliometric indicators may provide first insights in this respect, it is acknowledged that these indicators are likely to miss the economic performance associated with the use of that knowledge (*ibid.*). If, on the other hand, a product is in the focus, diffusion rates or market shares are proposed as indicators.[7] These two, however, are not suitable for emerging innovation systems, for which knowledge generation or the creation of variety may be much more important than diffusion. In such cases, Carlsson et al. (2002) therefore recommend a set of multiple, partly technology specific indicators that cover generation, diffusion and use of knowledge. Despite these propositions the authors clearly state the need for further research on performance measurement at the system level.

Interestingly, more recent conceptual articles on the analysis of innovation system have proceeded at the sub-system level instead (e.g. Bergek et al., 2005; Hekkert et al., 2007). This line of work takes into account that the outcome of an innovation system has many facets as it generates knowledge, develops and diffuses new technologies and products, supports institutional alignment, creates markets and the like (cf. Section 2.3). Several indicators or so-called diagnostic questions for different system sub-functions have been proposed for performance assessment, cf. Table 2.

Whereas for some functions, the identification of indicators seems to be straightforward this is not always the case. Hekkert et al. (2007), for instance, point out the difficulty to map resource mobilization in the context of the proposed method of event analysis and Bergek et al. (2005) highlight the complexity of functions like creation of legitimacy or creation of positive externalities and the corresponding challenge to arrive at clear-cut indicators. Moreover, Bergek et al. also include qualitative indicators whereas Hekkert et al. primarily focus on some sort of quantifiable measurements.

Furthermore, performance assessment at the level of sub-functions may also distinguish different phases of system development. In an early, so-called formative phase the importance of each of the sub-functions may be different from a later phase characterized by market growth and innovation diffusion (Bergek et al., 2005; Jacobsson and Bergek, 2004). System development over time is also related with the issue of how the sub-functions interact with one another and may eventually lead to virtuous cycles (‘motors’) or vicious cycles (e.g. Hekkert et al., 2007) or processes of ‘cumulative causation’ (Jacobsson and Bergek, 2004). Future research will most likely address these interactions and it will therefore contribute to closing the conceptual gap between performance of the sub-functions and overall system performance.

In sum, quite some progress has been achieved in order to make the innovation systems concept operational for the analysis of technological change. Further refinement and alignment, however, is needed with regard to (i) the systems concept as such (e.g. whether to include technology as part of the system or not), (ii) the issue of delineation (e.g. descriptive vs. conceptual delineation or a combination of the two), (iii) the analysis in terms of functions or activities (e.g. common set of functions, relationship between sub-functions and the function of the system as a whole) and (iv) performance assessment (e.g. indicators for different types of systems and different sub-functions). With regard to the analysis of radical innovation processes, we also have to take into account that (v) a more clear-cut distinction between the innovation part and the production part of the system is needed.

3. Multi-level framework for the analysis of technological transitions

The multi-level framework explains technological transitions by the interplay of processes at three different levels (e.g. Geels, 2002, 2005b). The key concept of the framework is the socio-technical regime, a coherent, highly interrelated and stable structure at the meso-level characterized by established products and technologies, stocks of knowledge, user practices, expectations, norms, regulations, etc. From the evolutionary perspective, a regime represents the selection environment for technological development in a certain field or sector, thus exerting a significant barrier for radical innovations to diffuse. Radical innovations may still occur, if they are protected by niches from the prevailing selection pressures. Niches represent the micro-level of the framework. The macro-level, the so-called landscape, includes a set of factors that influence innovation or transition processes but are hardly (or only in the long run) affected by themselves. Coherence of the regime is supported by its fit to the exigencies posed by external factors over the course of a specific historical time span. Landscape level factors, however, can and do change. They may therefore exert pressure on the regime. Such forces may weaken and destabilize a regime as they disturb the coherence of its elements. While under a strong and stable socio-technical regime, radical innovations have a hard time to diffuse beyond the niche-level, they may eventually break through when the regime is weak. Such a transition process, or regime shift, involves changes in technologies and technical artifacts as well as in user practices,

[7] This can even be complemented by studies on the revealed competitive advantage in a specific industrial field - if statistic data are readily available (*ibid.*).

Table 2
Proposed indicators for measuring performance at the level of sub-functions of innovation system

System function	Hekkert et al. (2007)	Bergek et al. (2005)
Entrepreneurial activities (Hekkert et al.); Entrepreneurial experimentation (Bergek et al.)	No. new entrants; no. diversification activities of incumbents; no. experiments	No. of new entrants and diversifying established firms; no. different types of applications; breadth of technologies used
Knowledge development	R&D projects; patents; R&D investments	Bibliometrics; number, size and orientation of R&D projects; patents; learning curves
Knowledge diffusion	No. workshops; conferences; network size and intensity	
Guidance of the search	Targets set by governments; no. press articles that raise expectations	Belief in growth potential; incentives from taxes (factor prices); regulatory pressure; expression of interest of leading customers
Market formation	No. niche markets; specific tax regimes; environmental standards	Market size; customer groups; actor strategies; role of standards; purchasing processes; lead users
Resources mobilization	[Whether or not inner core actors perceive resource access as problematic]	Volume of capital and venture capital; volume and quality of human resources; complementary assets
Creation of legitimacy	Rise and growth of interest groups and their lobby actions	[Alignment with current legislation; standards; visions and expectations; depiction in newspapers]
Development of positive externalities	–	[Political power; resolution of uncertain-ties; pooled labour market; specialized intermediaries; information flows]

policies, markets, industrial structures and supporting infrastructures (Geels, 2002). In particular, transitions encompass changes both *across* a particular value chain (vertical change) and *in each part* of the value chain (horizontal change) (Markard and Truffer, 2006). In fact, they might even change the entire configuration of an established value chain.

In the following section, we will reflect the key concepts of the technological transitions literature and discuss the issue of how to empirically define and delineate a socio-technical regime. A similar analysis could be carried out for niches and even for the landscape level. In this section, however, we restrict the discussion to regimes, from which much can be transferred to the other conceptual levels.

3.1. Key concepts

3.1.1. Socio-technical regimes

At the core of the technological transitions literature is the concept of technological or socio-technical regimes.[8] Rip and Kemp (1998) defined a *technological regime* as the

> "... is defined as the grammar or rule set comprised in the complex of scientific knowledges, engineering practices, production process technologies, product characteristics, skills and procedures, and institutions and infrastructures that make up the totality of a technology ..." (Kemp et al., 2001; p. 272).

This conceptualization emphasizes the institutional character of a regime as an emergent, collective outcome that cannot be changed at will (Kemp et al., 2001). In fact, the regime is narrowed down to a coherent set of rules, which materialize in the form of production process technologies and products as well as engineering practices, search heuristics, user practices, etc. This concept is different from the regime notion of Nelson and Winter (1982) with its focus on search and design heuristics or the one of Malerba and Orsenigo (1993) emphasizing knowledge related characteristics in order to explain differences in sectoral innovation patterns. The regime concept of Rip and Kemp is broader and also highlights demand aspects and societal issues (Kemp et al., 2001). Geels (2002) proposed to use the term *socio-technical regime* in order to make this distinction more prominent and to emphasize that not just engineers or scientists but all kinds of business people, end users, policy makers, societal interest groups, associations, etc. share the rules and practices that constitute a regime.[9] In all these defi-

[8] The regime notion has also been used in a broader way referring to the characteristics of e.g. policy processes ('policy regime') or research ('science regime') and the interaction and alignment of these different regimes (e.g. Geels, 2004; Fig. 5, Fig. 7). In the following, we concentrate on socio-technical regimes, even if we just use the word regime without the defining adjective.

[9] With regard to its texture, a socio-technical regime is conceptualized in terms of rules like in the original definition by Rip and Kemp

nitions, neither technologies nor actors or actor networks themselves are part of the regime. Rather, technologies and products *embody the rules* and actors *perform the routines* that make up the regime.

Against this background, other scholars in the field of technological transitions have widened the regime notion once again and included physical elements like artifacts and infrastructures (Hoogma et al., 2002; Raven, 2007; Smith et al., 2005) or even actor groups (e.g. Konrad et al., 2006; Verbong and Geels, 2007).

> "A technological regime needs to encompass both the paradigmatic framework of engineers and the system elements of a technology. The definition of technological regime we use is: the whole complex of scientific knowledge, engineering practices, production process technologies, product characteristics, skills and procedures, established user needs, institutions and infrastructures." (Hoogma et al., 2002; p. 19).

Interpreted in such a way, the regime has a conceptual composition, or *texture*, that is very similar to that of innovation systems, cf. Section 4.1. Here lies a major difference to Geels (2004, 2005b) who explicitly distinguishes socio-technical systems from socio-technical regimes and even from actors.[10] While this distinction is in line with earlier writings as it keeps the narrow regime definition in terms of rule sets, we think that it is not convincing with regard to the conceptual differentiation of system and regime.[11]

In sum, the technological transitions literature does not apply the concept of socio-technical regimes coherently. While there is a shared understanding in terms of regime characteristics (self stabilization, inertia, guidance of incremental innovation, etc.) the interpretation of *regime as a rule set* and *regime as a system* is quite diverse. We conclude from our survey of selected articles that there is a strong need to explicitly deal with actors, institutions and technological artifacts at the meso level. Some authors have responded to that need as they widened the regime concept in terms of components and others have explicitly introduced the notion of socio-technical systems. One issue that might improve clarity in this respect is the empirical delineation of regimes (Section 3.2). Another one is a cross-comparison of the different concepts within the multi-level framework and innovation systems approaches (Section 4).

3.1.2. Niches

Niches and the landscape are the complementary elements of regimes in the multi-level concept. Niches represent the local level of the innovation process and are commonly referred to as protected spaces or incubation rooms, in which new technologies or socio-technical practices emerge and develop isolated from the selection pressures of 'normal' markets or regimes (Geels, 2005b; Kemp et al., 1998).

> "A niche can be defined as a discrete application domain (habitat) where actors are prepared to work with specific functionalities, accept such teething problems as higher costs, and are willing to invest in improvements of new technology and the development of new markets" (Hoogma et al., 2002; p. 4).

While in an innovation studies context, novel technologies or products tend to be in the focus it has to be noted that niches may also host old technologies, which have existed for quite some time and are established in a stable niche environment. Two basic types of niches can be distinguished according to how its particular selection environment comes about. In the case of market niches, particular selection criteria have emerged, e.g. due to particular application contexts or consumer preferences that significantly deviate from 'usual' contexts or practices.[12] Market niches, in other words, can be regarded as some kind of 'natural anomalies' in regimes. Hoogma et al. emphasize that in market niches regular market transactions prevail as both producers and users of a new technology recognize its potential (Hoogma et al., 2002). Technological niches[13], on the other hand, have been

(1998). Later in the empirical part of the article, however, the regime notion is used more broadly including not only rules or institutions but also technological artifacts and actors (Geels, 2002, p. 1263).

[10] This clear distinction, however, is not consistent throughout Geels' publications (for an exception see Geels, 2005a, Fig. 2 or Geels, 2006b).

[11] Here we just refer to three aspects of criticism without elaborating them in detail. First, Geels' system definition is formally based on resources (Geels, 2004). At the same time, he reduces the system to the interaction of technological artifacts and excludes institutions and actors, which is not coherent with the resources concept. Second, what remains in the system to fulfill a societal function if actors and institutions are formally excluded? Third, in the empirical depiction of socio-technical systems, the author includes typical regime elements like user practices, regulations, symbolic meaning etc. (Geels, 2005a, Fig. 1 or Geels, 2006a, Fig. 1).

[12] In the case of photovoltaics, mountain cabins that are not connected to the electricity grid represent an application context, around which a market niche for solar power evolved. A different market niche is constituted by pioneering customers who are willing to pay the extra costs for a roof mounted photovoltaic system.

[13] Technological niches for photovoltaics have been created, for example, by governmental support programs in the form of investment subsidies or fixed feed-in tariffs.

deliberately created by actors and are supported by specific institutions (e.g. Geels, 2005b). Such actors may include regime members as well as outsiders and policy makers as well as entrepreneurs or other actors. In technological niches, the potential advantages of the new technology are still uncertain and not yet shared among the niche promoting actors (Hoogma et al., 2002).

Niches and regimes have similarities in terms of texture if the wider interpretation of the regime concept is applied (see above). Still, niches are very different from regimes with regard to the level of aggregation and stability:

> "... technological niches and sociotechnical regimes are similar kinds of structures, although different in size and stability ... Both niches and regimes have the character of organizational fields (community of interacting groups). For regimes, these communities are large and stable, while for niches they are small and unstable. Both niche and regime communities share certain rules that coordinate action. For regimes these rules are stable and well-articulated; for niche-innovations, they are unstable and 'in the making'." (Geels and Schot, 2007; p. 7).

The relationship between a niche and the regime may crucially determine the development of the niche, i.e. its eventual decline, stabilization or break through. Niches that are somehow compatible with the regime or have the potential to resolve bottlenecks of the regime may be more successful than others. Criteria like compatibility or solution potential, however, have to be made operational and common dimensions are needed in order to compare regimes and niches. Such dimensions may include socio-economic innovation and technology characteristics, institutions, actors, user practices, resources, etc. Which of these dimensions are important in this respect still remains an issue for further investigation. The same holds true for the interaction of niches and regimes in general (Berkhout et al., 2004).

3.1.3. Landscape

The landscape represents the external environment of processes and factors that influence both regimes and niches. In the literature, the landscape has been defined as a

> "... set of heterogeneous factors, such as oil prices, economic growth, wars, emigration, broad political coalitions, cultural and normative values, environmental problems." (Geels, 2002; p. 1260).

In a similar vein, Kemp and Rotmans (2005) conceptualize the landscape as background variables, which channel transition processes but are largely independent and autonomous. In a more general way, we can regard the landscape as the set of residual[14] factors that have an impact on innovation and production processes without being influenced by the outcome of innovation processes on a short to mid term basis. Geels and Schot (2007) elaborates further on the landscape concept, which he assigns an influence in the form of "deep-structural 'gradients of force' that make some actions easier than others". He furthermore differentiates landscapes in terms of basic dynamic patterns including regular change, specific shocks, disruptive change and avalanche change.

3.2. Empirical delineation of regimes

Some empirical studies apply the regime notion in a rather descriptive way as a synonym for sector (e.g. Raven, 2004), or just in the form of a catchword, e.g. medical regime, housing regime, agriculture regime (e.g. Geels, 2005a, 2006b). Using the notion in such a way makes little use of the strengths of the regime concept. While it may be sufficient in order to point to some general characteristics or the inertia of a sector, more effort will be needed if, for instance, the interaction of different regimes, or the shift from one regime to another one, is to be addressed. To increase the conceptual rigor in the identification and delineation of a regime is certainly crucial in this respect.

Defining and delineating a regime is challenging because different levels of analysis seem to be suitable in many empirical cases (cf. Berkhout et al., 2004). Socio-technical regimes may be defined at the sectoral or sub-sectoral level or at the level of particular technologies. In the field of electricity supply, for example, one might want to refer to the dominant regime of centralized power generation in order to highlight the radical nature of decentralized power generation, which currently just exists in niches. Alternatively, one might distinguish major fuel options and co-existing regimes of nuclear energy carriers, fossil fuels and renewable energy sources. Similarly, we could also differentiate regimes on the basis of conversion technologies, e.g. nuclear power reactors, steam turbines, hydropower turbines, may be even wind turbines.

Against the background of these challenges it is not surprising that many articles, although explicitly based on the multi-level concept, have not proven to deal very

[14] With 'residual' we mean factors that influence innovation and production processes but can not be reasonably allocated to the niche or regime level.

carefully with the regime concept in empirical terms. They say little about how regime(s) were delineated empirically (e.g. Geels, 2002, 2006a,b; Raven, 2004) or what constitutes the regime before and after a transition (e.g. Geels, 2005a). Moreover, there is no reflection or even justification why the regime notion has been applied in a certain way, e.g. at the level of industrial sectors in a selected country (Raven, 2004, 2007; Verbong and Geels, 2007).

Lately, however, some articles have explicitly picked up the issue of delineation (Geels and Schot, 2007; Konrad et al., 2006; Smith et al., 2005). Smith et al. (2005) suggest to distinguish different levels of analysis, i.e. regimes and so-called subordinate regimes. The authors also introduce the notion of embryonic regimes for regimes that are in an early state of development. Geels and Schot (2007) refer to the discrimination of different organizational levels and claims that "transitions in socio-technical regimes are situated at the level of organizational fields" (p. 402), which means that not only a single population of actors is involved but a broader community of actors.

In our view, both propositions still leave some aspects unresolved. First, a distinction of regimes and sub-ordinate regimes neglects that regime definition is not just a question of the appropriate aggregation level but also a question of perspective. Whereas one perspective, for example, may highlight structural characteristics and focus on a particular configuration (e.g. centralized structure of power supply), another one may concentrate on technological characteristics (e.g. regime of nuclear power generation). Second, making reference to terms like 'organizational field' or 'sectoral level' does not provide more than a general orientation because such concepts or reference points are similarly broad and empirically under defined.

As an alternative, Konrad et al. (2006) suggest

> "... to identify regime boundaries according to the density and strength of couplings between the elements of socio-technical configurations." (Konrad et al., 2006; p. 6).

The idea is to define a regime on the basis of couplings that are dense and hardly substitutable, while the couplings to elements outside a regime are less strong. This approach is well comparable to what we labeled conceptual delineation of innovation systems (Section 2.2). As a second pillar for the definition of a regime, the authors claim that the regime as a whole has to fulfill a societal function, by which they mean generic functions such as energy supply, housing, transportation, etc. One consequence of this proposition is that what is empirically regarded as a regime strongly depends on the definition of generic societal functions. Another consequence is that a regime could not be conceptualized as a rule set any more but had to be defined in the wider way. We think while the link between regimes and societal functions might be useful for particular research questions, the regime concept should rather not be defined or delineated on this basis.

Against this background, we may conclude that there is no unambiguous regime definition. Regimes can be defined at different levels of aggregation and from different perspectives and the choice of a particular level depends to a large extent on the research question. Still, the use of the regime concept in empirical studies should be justified and made as clear and explicit as possible in order to fully unfold the analytical power of the concept and to allow for a cross comparison of case studies. Moreover, defining a regime should be guided by the intention to use its conceptual strengths and key features most effectively. These features certainly include (i) the regime structure, i.e. the strong linkages between their elements which account for the stability of socio-technical configurations (Geels, 2002); (ii) the multi-dimensionality of socio-technical regimes, i.e. the fact that they encompass different dimensions such as technology, user practices, application domains, symbolic meaning of technology, infrastructure, industry structure, policy issues and particular stocks of knowledge (Geels, 2002) and (iii) their influence on innovation processes as they channel and determine the development and use of technologies (Rip and Kemp, 1998) and function as a selection and retention mechanism but still generate incremental innovation (Geels, 2002) and therefore stabilize certain technological trajectories.

4. Comparison of the key concepts

In this section we compare the key concepts in the literature on innovation systems and transitions to address the issue of how they are related and how they might complement each other. We analyze technological systems, sectoral systems of innovation, socio-technical regimes and niches with regard to their basic concepts, the empirical level of aggregation that is typically applied and their relation with innovation and transformation processes, cf. Table 3. As a result of this comparison, we summarize the strengths and weaknesses of both strands of literature.

Table 3
Comparison of key concepts

	Basic concept	Level of aggregation	Role for innovation
Technological system (TS)	Actors, networks and institutions (Jacobsson and Bergek, 2004)	High to medium (technologies, multiple application contexts)	'*Innovation part*': generation, diffusion and use of new technologies '*Production part*': diffusion and utilization of established technologies
Regime	Set of rules carried by different social groups (Geels, 2002)	High (industries, sectors)	Guidance of innovation processes: Selection of incremental improvements of established products over entirely new products or technologies
	Knowledge, practices and procedures, user needs, institutions, technologies and infrastructure (e.g. Hoogma et al., 2002)		
Niche	Actors, networks, supportive institutions (external) (Hoogma et al., 2002)	Low (innovation networks, single application context)	Provision of alternative selection environment and thus protection of innovations

4.1. Commonalities and differences

In terms of basic concept, both innovation system concepts (TS, SSI) and niches have commonalities as they all regard actors, networks and institutions as important conceptual components. But they are also slightly different as the SSI concept additionally encompasses products, technologies and processes. And niches are also a little different because supportive institutions are rather external elements, not part of the niche. The regime concept, in contrast, has a different texture – at least in its narrow interpretation as a rule set. However, in its broader definition (cf. Hoogma et al., 2002), the regime has been used rather similarly to the SSI concept. Due to these similarities in terms of texture and key components, it seems legitimate to directly relate and compare the four concepts.

With regard to the typical level of aggregation (cf. Sections 2.2 and 3.2), the comparison shows that SSI and regimes are defined at similar empirical levels, i.e. at the level of industries or sectors. Note that SSI may as well encompass more than one regime. In a similar vein, *mature technological systems* may also be defined at a high level of aggregation although they may reach across sectors (cf. Fig. 1). *Emerging technological systems*, however, are typically analyzed at a medium level of aggregation, i.e. they encompass several application contexts of the novel technology. Niches, finally, are the least aggregated and mostly just refer to a single application context. Technological innovation systems, in other words, may be regarded as to encompass several niches. In Fig. 3. we depicted the different levels of analysis of the four concepts based on a figure in Geels (2002). In the case of stationary fuel cells, for example, there are niches such as small fuel cell systems for residential buildings and mid-sized fuel cells for public facilities like hospitals or administration buildings. Technology development in this field is influenced by the established regime structures of centralized electricity generation and also subject to landscape factors such as energy prices. At the sectoral level the SSI on mechanical engineering and also the chemical sector are involved in technology development. And at the level of technological systems, we might differentiate the technological system of stationary fuel cells and the one of mobile fuel cells, which again may relate to different regimes and sectors (e.g. the automobile sector).

With regard to their role for the innovation process, regime and niche are certainly the most differing concepts. While regimes generate incremental innovations that strengthen the regime, niches create and protect radical innovations, which may lead to destabilization and far-reaching changes in established regimes. TS, on the other hand, do not make a difference between radical and incremental innovations, i.e. they – implicitly – embrace the production *and* the innovation part. The TS concept therefore can be applied to both, regime- or niche-like empirical situations. Although SSI formally differentiate between production and innovation, in practice the concept tends to focus on incremental innovation activities.

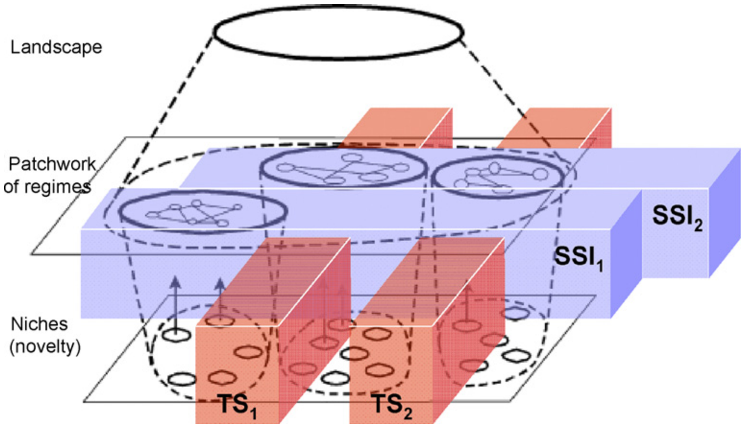

Fig. 3. Interrelation between technological systems (TS), sectoral systems of innovation (SSI) and the multi-level framework (adaptation of Fig. 3 in Geels, 2002).

If the focus is on the production part of TS or SSI, both concepts can be regarded as structures that stabilize and support established technologies and products and continuously improve them along specific trajectories. In this case they play a similar role as regimes, i.e. providing guidance to innovation processes. If the focus, however, is on the innovation part, especially TS are similar to niches as they protect and generate innovations. Edquist's general definition of innovation systems – in which he states that they develop, diffuse and use innovations – is very much in line with this interpretation (Edquist, 2005). Whether a TS is regime-like or niche-like certainly depends on its maturity, i.e. an immature TS in an early, or formative, phase of development (cf. Bergek et al., 2005) is rather niche-like while a mature TS develops more and more features of a regime (cf. 'cumulative causation', Jacobsson and Bergek, 2004).

4.2. Strengths and weaknesses

The strength of the multi-level framework is that innovation and transition processes can be explained by the interplay of stabilizing mechanisms at the regime level and (regime-) destabilizing landscape pressures combined with the emergence of radical innovations at the niche level. Thereby, the framework also leaves room for contingencies such as external shocks or disruptive changes at the landscape level (e.g. Geels and Schot, 2007). The approach, however, is less powerful when it comes to the roles and strategies different actors play in such processes, the interaction (dual relationship) of actors and institutions or the agency enjoyed by different actors or actor groups (e.g. Smith et al., 2005). This again relates to the issue of how resources are distributed among actors, how resource endowments explain the development of networks and the innovation potential of actors (cf. Markard and Truffer, in press).

Moreover, the multi-level approach is largely confined to the niche level in its analysis of emerging novelties. This is problematic for three reasons. First, there is quite a gap in terms of process complexity and aggregation between niche and regime and little explanation for dynamics beyond the niche level such as complementary effects of developments in different niches or the emergence of niche transcending institutions. The analytical distinction between technological and market niche together with the rather diffuse concept of 'niche-accumulation' represent first propositions to bridge this gap (Geels and Schot, 2007). Second, the concepts and tools to investigate innovation dynamics at the niche level are less elaborated than those developed for the study of innovation systems. A recent attempt to cope with the latter challenge is the suggested distinction of learning, network creation and formation of expectations as three key processes for the analysis of niche level dynamics (Geels and Raven, 2006; Geels and Schot, 2006). Little has been said, however, why these particular processes should receive particular attention. Finally, actors and strategy making have received little attention in the conceptualization of niches.

Against this background the innovation system concept provides more analytical power with its elaborated framework of structural and functional analyses, which are well complementary (e.g. Bergek et al., 2005; Markard and Truffer, in press). Furthermore, it is a meso-level concept that reaches well beyond niche level processes. It also has the potential to deal more explicitly with firm strategies and agency (Markard and Truffer, in press).

The innovation systems approach, however, may be characterized as myopic with regard to the explanation of technological transitions. The success of innovations is mainly regarded as a consequence of the performance of the corresponding innovation system. The systems perspective, in other words, is inward oriented and does not pay much attention to the system's environment. As a consequence, external institutions which, for example, hinder the innovation process are just treated as blocking mechanisms although they may be much more than that, e.g. the result of strategic intervention of incumbent actors. Here lies strength of the regime notion, which explains such strategic reactions or the difficulty of institutional changes due to a high degree of interrelatedness. Moreover, the systems approach runs the risk to miss influential processes because the review of the environment is less systematic. In a similar vein, novel technologies or products that emerge in competing innovation systems and thus affect the innovation under study may be neglected in the analysis.

5. Towards an integrated framework for the analysis of innovation processes

The innovation systems approach and the multi-level framework represent different perspectives on processes of innovation and socio-technical transformation. They are however comparable in terms of basic concepts and theoretical roots, they share a number of similarities and they have complementary strengths. Especially the latter aspect leads us to conclude that a combined framework may offer benefits that – for certain analytical tasks – reach beyond the merits of each approach. To develop such a combined framework represents an endeavor that exceeds the limits of the current paper. In particular, such a proposal would need a number of empirical test cases to demonstrate its relative advantages compared to both approaches on their own. Still, on the basis of the above review of recent innovation system and transition research, we can briefly summarize a number of conceptual issues a combined framework should strive to address. Moreover, we propose a specific definition of technological innovation systems that would ease the translation of results from studies carried out with a multi-level perspective.

In order to not become overly complex or to create overlaps a combined framework should clarify the relevance, need and application domain of each of its conceptual elements. The elements should be defined in a way as to not cut across one another and the general relationships between the different elements should be clarified. More specifically, such a framework should be applicable to different kinds of innovations and it should capture innovation dynamics at different levels, e.g. strategy formation and interaction of actors as well as the emergence and growth of the innovation system as a whole. Finally, a combined approach will be highly beneficial if it meets some or all of the aspects identified as shortcomings of one of the frameworks (cf. Section 4.2):

- consider more explicitly innovation processes as perceived at the micro-level of organizations (strategies, agency),
- take into account mutual interdependencies between actors and institutions,
- develop consistent performance comparisons in order to recommend how to support the development of particular innovations,
- facilitate systematic identification and assessment of the broad range of factors (events, developments, institutional effects, actor behavior, etc.) that influence innovation processes.

Our analysis has also shown that a major challenge for a combined framework will be the fact that the prevailing definitions of TS and SSI comprise characteristics of both, niches and regimes. The distinction between production systems, incremental innovation processes and radical innovation structures is mostly not very clear-cut. So the creation of entirely new products or technologies and the utilization of established ones may occur simultaneously in a system. This conceptualization will pose analytical difficulties especially in the case of radical innovations, for which established production systems often create formidable barriers. Therefore, radical innovations are often promoted by actor networks that show little overlap with prevailing actor structures in a sector or technological field. If conceptually we try to define innovation systems in a way that they encompass also opposing actors, outsiders and critics of a certain technology, the innovation system concept will probably degenerate into a merely descriptive bracket for very different processes and structures. As a consequence, it would loose almost every explanatory power.

We therefore propose a definition of the innovation system concept based on the following: (i) It concentrates on the innovation function of the system (cf. Edquist, 2005), (ii) applies a technology specific (or product specific) perspective[15] (cf. Bergek et al., 2008;

[15] With this second aspect we want to emphasize that a specific innovation is at the core of the system, not a sector. Such a specific

Hekkert et al., 2007) and (iii) restricts the system to actors, institutions and networks that are supportive[16] to the innovation process, i.e. that share the goal of furthering at least some variant of the socio-technical configuration. For this concept, we suggest the particular notion of *technological innovation systems*.

> A technological innovation system is a set of networks of actors and institutions that jointly interact in a specific technological field and contribute to the generation, diffusion and utilization of variants of a new technology and/or a new product.

We suggest applying this notion in a conceptual, not in a descriptive way. This implies that we do not expect to find a technological innovation system (TIS) in every arbitrarily chosen innovation field. There may be empirical cases, in which just small innovation networks or niches exist that have not developed any internal institutions. Such a network of actors would not qualify as a TIS although it might do in the future. In other words, we interpret the TIS as a model that applies for innovation fields during a certain period of time in the development of the corresponding technology. With reference to Bergek and colleagues (e.g. Bergek et al., 2008; Bergek and Jacobsson, 2003) we might say that a TIS begins at some point in the formative phase and ends at some point in the growth phase. In our reading, a TIS has to meet a set of minimum conditions, for which we propose the following, preliminary list:[17]

a. A TIS encompasses a variety of different actors in the sense that they pursue different innovation strategies and/or control a set of different resources. These actors are united by shared expectations or a shared vision for the respective innovation field.
b. Actor structures within the TIS are characterized by a certain division of labor. This means that we may typically identify an 'innovation value chain' or rather innovation networks with different types of actors (firms) focusing on different innovation tasks.
c. A TIS is characterized by a variety of institutions. A key characteristic of TIS is 'internal' institutions[18] that have emerged as a result of activities (e.g. lobbying, expectation management, negotiation of internal standards) of system actors.
d. The TIS is also characterized by a certain degree of market transactions, although the market might be immature. A key feature of these transactions is a number of different, competing suppliers among which customers can choose.

Defined and identified in such a way, a TIS can be considered to interact with one or more socio-technical regimes, cf. Fig. 4. Take again the case of stationary fuel cell technology (Markard, 2008), which interacts with the structures of centralized electricity generation ($Regime_1$) and decentralized boilers for heating ($Regime_2$). The regimes may represent barriers for the development and diffusion of the innovation and, at the same time, they may be challenged by the innovation as it represents a potential substitute for established products or technologies. Depending on the institutional overlap or the shared set of actors of a TIS with a certain regime, resistance will be more or less intensive.

Moreover, the focal TIS is likely to interact with other TIS such as the field of mobile fuel cells in our example. There are two basic modes of interaction: competition and complementation. If the products or technologies in two TIS serve similar purposes in similar application contexts, the interaction will have a competitive character. If, on the other hand, the innovations support each other, e.g. like network technologies, the interaction is rather complementary. Note that even a competitive technology may have a complementary effect, if it contributes to the weakening of prevailing regimes. These interactions may be mediated by organizations that are part of several TIS at the same time. For instance research institutes, consultancies or certain government offices, which have to manage entire portfolios of technologies, are organizations that may be involved in different TIS simultaneously. At the landscape level, factors such as electricity market liberalization or the prices for electricity and natural gas influence the TIS (and the regimes) in the case of fuel cells.

Finally, a TIS usually encompasses several niches or application contexts such as small and mid-sized stationary fuel cell systems.[19] A TIS is, however, in general

innovation does not necessarily have to be a technological innovation. In this paper, however, we said to concentrate on new technologies or (technology based) products.

[16] This means that opponents or institutional barriers are not part of the system.

[17] Note that for our idea of temporary existence of TIS we would also have to define conditions that define the end point. This has to be left to later research.

[18] Other institutions may be regarded as external. We define external institutions as those that were not primarily initiated by actors of the TIS. External institutions are somehow independent of the system, i.e. they are not directly affected by the innovation success. Still, they are crucial as they stabilize and protect the TIS.

[19] Niches, however, are not necessarily a fully integral part of a TIS as Fig. 4 suggests. A niche may also relate to other TIS thus bridging different innovation systems.

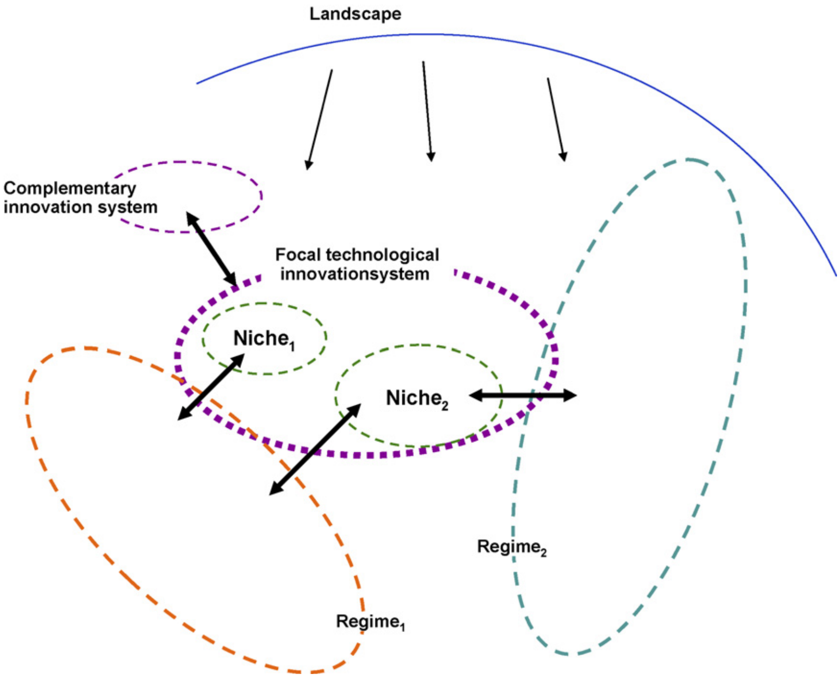

Fig. 4. Technological innovation system and interactions with the conceptual elements of the multi-level framework.

more than the sum of its niches because there may be additional endogenous institutions that stabilize the TIS (e.g. expectations on the future of fuel cell technology in general) or actors, which do not engage in the context of a niche but still contribute to the TIS (e.g. industry associations). Niches are typically important testing fields around which actors of a TIS assemble and coordinate their actions. Niches may even be sites where actors (and technologies) from different TIS meet and exchange their projects. As niches grow or branch into new ones the corresponding TIS may grow and mature, too.

The use of clearly defined and mutually compatible terms is certainly a first necessary step on the road to an encompassing theoretical framework of socio-technical change. However, further conceptual advances are needed. While innovation system concepts, for example, promise to more explicitly deal with innovation activities and strategies of actor groups, an explicit concept that permits to deal with innovation processes at the level of business units and at the system level still remains to be worked out (cf. Markard and Truffer, in press). Of particular interest would be mechanisms that lead to the emergence and the prospering of TIS. Here an explicit analysis of dynamics and social construction processes is necessary. Further issues to be clarified are implications for policy and strategy formulation, performance comparisons of innovation systems, the identification of alternative trajectories for specific radical innovations, etc.

6. Summary

The innovation systems approach and the multi-level frameworks have both been applied for the study of radical innovation and transformation processes of socio-technical configurations. So far, there has been little overlap in the use of these frameworks although they are based on common theoretical roots and offer promising complementarities. In this article we have reviewed the state of the art in both fields and, on the basis of a comparison, identified similarities, conceptual overlap, strengths and weaknesses. This led us finally to outline an overarching conceptualization which would build on the complementarities between the two traditions and allows combining their strengths. As a necessary step towards an integrated framework, we proposed to define a technological innovation system in a way that is compatible with the multi-level concept. On the basis of this definition, a combined framework may be elaborated, which encompasses four major conceptual elements. Niches or application contexts, in which radical innovations emerge and mature; a technological innovation system, which might encompass niches and is characterized by emergent institutions and conjointly produced resources; socio-technical regimes that represent the dominant production structure, which challenges the TIS; and a landscape with parameters that influence regimes and innovations without being influenced in turn. The environment of the TIS is composed of regimes, competing and complementary technological innovation systems and landscape level influences.

In our view, such a framework can offer a series of benefits. In general, it ties together two so far not very much related strands of innovation literature thus facilitating a seamless translation of results gained from one perspective into the other. This seems all the more fruitful as the benefits of both, the multi-level concept and the innovation systems approach can be exploited. A combined framework, more specifically, allows addressing the particularities of radical innovation as it provides a clear distinction between the innovation part of a system and its production part. From the perspective of the technological transitions literature, the framework offers the possibility to account for emergent effects in innovation processes that occur beyond individual niches. It also provides a basis for an actor oriented analysis of innovation processes, which explicitly considers different actor strategies, resource endowments and agency. Furthermore, the framework facilitates performance analyses on the basis of functions as it makes a clear analytical distinction of system structures and functions.

From the perspective of the innovation systems literature, the multi-level framework represents a complement with regard to the conceptualization of the interactions of the system and its environment. The growth of a TIS including processes such as niche branching and accumulation, institutional alignment or the entry of actors may become a powerful model for the explanation of technological transformations or even transitions. Moreover, the system environment in terms of socio-technical regimes and interacting technological innovation systems can be explored in a much richer way than before. This might also facilitate the definition of system boundaries. Finally, the niche concept also offers a specific focus on contexts, in which particular kinds of institutionalization processes occur. In this context, the framework also offers a conceptual model for the analysis of immature innovation fields, for which niches might well be observed but an entire TIS does not yet exist.

Despite these promises the framework still has to be refined further and applied to an increasing set of empirical cases. Up to now, four studies have been carried out in our research group in different innovation fields including smart buildings (Konrad, 2006), stationary fuel cells (Markard, 2008), biogas power plants (Markard et al., submitted for publication) and membrane technology in the sanitation sector (Wegelin, 2006). These studies helped us to elaborate the ideas presented in this article but they do not yet represent real test cases for the framework. Future analyses therefore will be needed that are very explicit about their conceptual basis and carried out in a way as to systematically explore the benefits or difficulties of such an integrative framework.

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