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Comparing systems approaches to innovation and technological change for sustainable and competitive economies: an explorative study into conceptual commonalities, differences and complementarities

Lars Coenen (lars.coenen@circle.lu.se)
CIRCLE, Lund University

Fernando J Díaz López (fernando.diazlopez@tno.nl)
TNO Innovation and Environment, Netherlands

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Centre for Innovation, Research and Competence in the Learning Economy (CIRCLE)
Lund University
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Comparing systems approaches to innovation and technological change for sustainable and competitive economies: an explorative study into conceptual commonalities, differences and complementarities

Coenen, Lars and Díaz López, Fernando J.

Abstract

This paper makes a distinction between three theoretical frameworks that have been highly influential in the discourse on innovation, competitiveness and sustainability: sectoral systems of innovation (SSI), technological innovation systems (TIS) and sociotechnical systems (ST-Systems). These frameworks share a common systems approach to innovation but are often positioned as different bodies of literature that correspond to different epistemic communities. This paper is explorative and conceptual in nature. It presents a systematic comparative review of SSI, TIS and ST-Systems based on the following analytical dimensions: (1) system boundaries, (2) actors and networks, (3) institutions, (4) knowledge, and (5) dynamics. In the concluding section commonalities and differences, of the three approaches are presented and suggestions for complimentarily are made.

Keywords: : Innovation Policy, Innovation System, Governmental Activism, Governmental Experimentalism

Abstract

This paper makes a distinction between three theoretical frameworks that have been highly influential in the discourse on innovation, competitiveness and sustainability: sectoral systems of innovation (SSI), technological innovation systems (TIS) and socio-technical systems (ST-Systems). These frameworks share a common systems approach to innovation but are often positioned as different bodies of literature that correspond to different epistemic communities. This paper is explorative and conceptual in nature. It presents a systematic comparative review of SSI, TIS and ST-Systems based on the following analytical dimensions: (1) system boundaries, (2) actors and networks, (3) institutions, (4) knowledge, and (5) dynamics. In the concluding section commonalities and differences, of the three approaches are presented and suggestions for complimentarily are made.

Keywords: technological change, ecological modernisation, innovation systems, socio-technical systems, sustainability and competitiveness.

Introduction

There is an increasing support among policy-makers and researchers for the notion, raised under the banner of ecological modernisation [1], that clean technology and smart innovation development and diffusion are key to create a win-win situation: maintain and/or improve economic competitiveness and secure environmental sustainability of different sectors and the economy as a whole [e.g. 2, 3-9]. For example, the Swedish presidency of the EU in 2009, maintains that Europe needs to make a shift to an eco-efficient economy. This vision conveys the ambition to create more wealth while using less natural resources and causing less negative impact on the environment. A clear focus on research, innovation, development and demonstration is considered to be one of the cornerstones to achieve this win-win situation [10]. The OECD, aligned to their green growth strategy [11], has also devoted efforts to analyse how eco-innovations come about and what policy instruments are best placed to promote a fairer and more competitive and sustainable economy [12, 13]. The emphasis on innovation has contributed to transcending classical policy boundaries between e.g. industrial policy, environmental policy, science and technology policy [14]. On the other hand, its popularity runs the risk of degenerating the concept into a panacea that is supposed to solve all problems at the same time without paying due respect to the nature of the challenges that are raised.

This paper identifies three theoretical frameworks which have been highly influential in the discourse on innovation, competitiveness and sustainability[1]: sectoral systems of

[1] The paper serves as a preparatory conceptual exploration to conduct an analysis of the impact of the Dutch energy transition in terms of sustainability and competitiveness. This policy program seeks to safeguard a sustainable national energy economy. Innovation in renewable energy sources and reduction of energy consumption is regarded as a driving force to achieve the three functional goals to the program: (1) reliable provision of energy services, (2) low prices thanks to economic efficiency and market dynamism, (3) minimal negative environmental and social impacts [24]. To highlight the transcendental character

innovation (SSI), technological innovation systems (TIS) and socio-technical systems (including transitions) (ST-Systems). These frameworks share a common systems approach to innovation but are often positioned as different bodies of literature that correspond to different epistemic communities [15]. In the SSI literature innovation is primarily seen as a means for firms and industries to achieve competitiveness. Following the definition set by the European Commission competitiveness is seen as the ability to produce goods and services which meet the test of international markets, whilst at the same time maintaining high and sustainable levels of income, or more generally, the ability to generate, while being exposed to external competition, relatively high incomes and employment levels [16]. In an increasingly globalising knowledge-economy, competitiveness is derived from differentiated capabilities to innovate [17]. In somewhat similar vein, the original purpose of studies of technological innovation systems has been to show how technological innovation gives rise to economic growth (at the aggregate level). However, recent contributions in this area of research have been more concerned with the emergence of clean technologies that address sustainability problems. The ST-System literature is first and foremost interested in how new configurations around large socio-technical systems emerge and retain in society. Empirically the framework has been mostly applied to systems that relate to sustainability such as energy and mobility. This focus is further strengthened in the more normative and applied notion of transition management. The term transition entails the broad, system-wide interaction and co-evolution of new technologies, changes in markets, user practices, policy and cultural discourses, and governing institutions [18]. Transition management, pioneered by authors

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of the program, six ministries work together: Economic Affairs; Housing, Spatial Planning and the Environment; Transport, Public Works and Water Management; Agriculture, Nature Management and Food Quality; Foreign Affairs; and Finance. This policy program is heavily influenced by the work of scholars in the Netherlands on innovation systems, socio-technical systems and transitions [20, 21, 31, 32, 53] such Rotmans [19] and Kemp [20, 21], aims to provide an analytical and policy framework to explain and govern these complex, co-evolving, structural societal changes [e.g. 22, 23-25].

Given these different yet in light of ecological modernisation related rationales for systems approaches to innovation and technological change, the ultimate objective of this paper is to systematically compare these approaches in order to arrive at insights on which dimensions the respective approaches differ or share commonalities and whether and how they can complement each other. Other scholars have reviewed (a selection of) these concepts [e.g. 26, 27, 28]. Insights from these contributions are gratefully acknowledged and provide useful input into the following analysis. However, a systematic comparative review of the SSI, TIS and ST-Systems concepts based on predefined dimensions has not been previously conducted. It is important to mention that this review has been primarily based on a set of pioneering contributions that have laid out the principle ideas, notions and terminologies of the respective approaches [namely 29, 30-32]. Nonetheless, where appropriate, we have also looked into other sources next to these seminal papers.

The following paragraph provides an introduction to systems approaches to innovation and presents the set of dimensions along which the SSI, TIS and ST-Systems concepts are subsequently analysed. This is followed by a section in which these three approaches are systematically compared. In the conclusion, in addition to presenting their commonalities and differences, scope for complementarities across the three approaches is outlined.

Systems approaches to innovation

Innovation refers to technologically novel or improved material goods, intangible services or ways of producing goods and services [33]. Cleaner technologies and methods are acknowledged as a common form of innovation, since they imply technological, organisational and institutional changes to the knowledge base of existing production systems [9, 34]. Innovations are iteratively enacted through networks of social relations, rather than through singular events by isolated individuals or organisations. To understand innovation as an inherently social, interactive learning process is the defining feature of the systems approach to innovation [35]. Moreover, the systems approach to innovation acknowledges that certain patterns of interaction are more pronounced than others because organisational behaviour and strategy is shaped (though not wholly determined) by various laws, rules, norms and routines (i.e. institutions). In short, a system of innovation is defined as networks of organisations and institutions that develop, diffuse and use innovations [26]. To single out which organisations and institutions are determinants of innovation and technological change and in what way, it is common to ex-ante delineate the system boundaries and its components.

There are various ways to discriminate between the system and its environment [36]. This is necessary to distinguish the endogenous drivers of innovation (those belonging to the system) from the exogenous drivers of innovation (those outside the system). According to Edquist [33] boundaries can be drawn: (1) geographically, or on the basis of (2) technological fields, (3) product areas and (4) activities. It is important to consistently consider the boundaries of the innovation system in order to avoid an explosion of possible factors and drivers for innovation. However it would be misleading to purely isolate the system from its environment [37]. Every system of innovation is situated within a certain context.

According to Edquist [38] a system of innovation is constituted of components of the system and the relations among the components. These components, in turn, refer to organisations and institutions. Liu and White [27] add to this a qualification between primary and secondary actors. Primary actors are those actors that directly perform innovation activities whereas secondary actors affect the behaviour of or interaction between primary actors. The role of institutions has also been extensively analysed and categorised. The literature is however still highly diffuse and heterogeneous in terms of institutional analysis of systems of innovation and technological change [e.g. 39, 40]. Commonly used and accepted distinctions are those between formal and informal institutions [41], regulative, normative and cultural-cognitive types of institutions [42], and different levels of institutional structures [43]. Institutions often work in a subtle way, as is emphasised by the notion of informal institutions. Habits, conventions and routines regulate social and economic life but being *"habitual patterns of behaviour embodying knowledge that is often tacit and skill-like"* [44] emphasises their often intangible character in contrast to the codified nature of formal institutions. Regulative institutions refer to the formal rules of the game that constrain behaviour and regulate interaction. They determine what is allowed and what is not allowed and are therefore often backed by sanctions. Examples are laws, contracts and norms. Normative institutions encompass informal rules that follow from socialisation processes and socially desirable expectations. They confer values, duties, responsibilities, which set out what is right and what is wrong. Cognitive institutions are the rules that *"constitute the nature of reality and the frames through which meaning or sense is made"* [32, p. 904]. Examples are cognitive frames, mental paradigms, visions, expectations, perceptions, etc. The different levels of institutional structures [43] draw attention to the different aggregation levels by which institutions work. Institutions can be conceptualised as single rules that more or less independently influence social and economic behaviour but also as semi-coherent arrangements that are mutually dependent and exert a specific influence through their interplay.

In a systems perspective to innovation, knowledge is seen as the most strategic resource and learning as the most fundamental activity [35, 45]. Despite a general agreement on the validity of this statement, knowledge and learning remain elusive concepts. Based on an extensive literature review Ibert [46] introduces the perspectives of 'knowledge' and 'knowing' as representing general intellectual strategies of understanding the peculiar ways human beings know. The former represents the rationalistic approach where knowledge consists of commensurable quanta or discrete entities that share commonalities with a commodity or an economic stock. Being knowledgeable means to 'possess' a large number of knowledge entities [47]. In contrast, 'knowing' reverberates an ability to act. It emphasises the collective nature of knowing and it is by default tied to social practice. Therefore knowledgeability stems from different practices which need to be translated across cultural and social boundaries rather than accumulated smoothly. Innovation systems, having been pioneered by the (albeit heterodox) economic disciplines has conceptualised knowledge and learning (knowledge accumulation) mainly from a rationalistic rather than a constructivist approach. Initially a lot of emphasis was given to R&D based innovation and measurable outputs such as patents. In a way, a high-tech fascination took a life of its own, limiting knowledge-intensive and innovative activities exclusively to high-tech industries such as pharmaceuticals and electronics. Currently there is increased attention for the importance of innovation in so-called low tech sectors [48], creative industries [49], non-technological aspects of innovation and organisational innovation [50].

Another dimension that is intrinsically connected to the systems of innovation approach is change and renewal. It is therefore somewhat ironic that the approach has received a fair amount of criticism for delivering static, snap-shot analysis [51, 52]. This static approach seems to be endemic to the focus given to the structure of the innovation system, i.e. the actors, network relations and institutions. In contrast, Hekkert, Suurs, et al. [53] and also Bergek et al. [54] have pushed the research agenda towards investigating the dynamics of innovation systems (see below).

On the basis of the above outline we have gathered the following dimensions which allow for a systematic comparison of various systems approaches to innovation and technological change:

1. System boundaries
2. Actors and networks
3. Institutions
4. Knowledge
5. Dynamics

A systematic comparison of systems approaches to innovation and technological change

Definitions and System Boundaries

The most comprehensive and up-to-date definition is probably given by Malerba [55, p. 16] in which a *"sectoral system of innovation and production is composed of a set of new and established products for specific uses, and a set of agents carrying out activities and market and non-market interactions for the creation, production and sale of those products"*. In this, a sector is a set of activities that are unified by some linked product groups for a given or emerging demand and which share some common knowledge [56]. This definition acknowledges the often intrinsic ties between production and innovation activities. However, Malerba [55] acknowledges that the innovation system can be seen as an analytically separate system. In the general understanding of this body of literature, the innovation system has also received most attention. In terms of boundary setting, the approach provides clear product-based guidelines. Sectoral systems of innovation can therefore include multiple technologies and transcend geographical boundaries. The emphasis on product-groups, e.g. automobiles, chemicals, construction, provides a useful connection to the NACE nomenclature which is the standard statistical classification of economic activities within the European Community. This facilitates the use of statistical data to analyse sectoral innovation patterns in a coherent way. However, the way SSI sets boundaries on the basis of existing products may provide difficulties in the case of emerging demand and products (e.g. in the case of biotechnology or fuel cells). Due to this state of emergence, there is considerable technological and market uncertainty. How markets will develop and which users will adopt the technology is still an open-ended question. Ex-ante boundary setting of the system may therefore miss out on important factors and actors driving innovation.

The Technological Innovation System approach appears to be better equipped to deal with this state of emergence [57]. Pioneering work on TIS was carried out by Bo Carlsson and Rikard Stankiewicz [30]. They define it as: *"network(s) of agents interacting in a specific economic/industrial area under a particular institutional infrastructure or set of infrastructures and involved in the generation, diffusion, and utilisation of technology. Technological systems are defined in terms of knowledge or competence flows rather than flows of ordinary goods and services. They consist of dynamic knowledge and competence networks"* [30, p. 111]. This definition acknowledges that a technological system can be national, regional and international, and, that a technology can cut across various industrial sectors. Biotechnology, for example, is used by the pharmaceutical industry but also in food, textiles, agriculture and even mining. Given that technology is the common denominator in TIS, this allows for a framework geared to studying how the configuration of actors, networks and institutions change over time as the technology develops [58]. Recently, the emphasis on dynamic analysis of TIS have received considerable impetus by explicitly focusing on the functions or processes taking place within the system of innovation [53, 54]. It remains however a little ambiguous how exactly the boundaries of a technological domain are set.

Above approaches have been criticised by proponents of socio-technical systems for focusing exclusively on the production side and putting an analytical premium on firms [32]. Instead, they argue, ST-systems encompass production, diffusion and use of technology in relation to so-called societal functions (e.g. transport, communication, nutrition). The elements of these systems, which in the above approaches are mainly constitutes of organisations, include for ST-systems also artefacts, knowledge, capital, labour, cultural meaning, etc. An important distinction within ST-systems is that between regimes and niches. Hoogma, Kemp et al. [59, p. 19] define a regime as: *"the whole complex of scientific knowledge, engineering practices, production process technologies, product characteristics, skills and procedures, established user needs, institutions and infrastructures".* The 'structuration' of this complex is high, providing stable rules and coordinating effects on the actors that are implied by the regime. *"Technological niches and socio-technical regimes are similar kinds of structures, although different in size and stability"* [60, p. 7]. This means that a regime and niche, in principle, are based on the same definition. However, 'structuration' in niches is looser, providing scope for heterogeneous rules and diffuse activities. This leads Geels [61] to argue that regimes generate incremental innovations as a result of stable and well-articulated rules whereas radical innovation belongs to the domain of unstable niches. Markard and Truffer [26] remain however critical of the inconsistent way that empirical studies of ST-systems have delineated the system, either using it in a rather descriptive way as a synonym for sector or just in the form of a catchword.

Actors and networks

To determine how the various approaches conceptualise the role of different actors in the system we draw on the aforementioned distinction between primary and secondary actors. Both SSI and (the pioneer work of) TIS can be regarded as firm-centred systems where the firm is the leading organisational unit responsible for innovation. *"Firms are the key actors in the generation, adoption, and use of new technologies, are characterised by specific beliefs, expectations, goals, competences, and organisation, and are continuously engaged in processes of learning and knowledge accumulation"* [55, p. 390]. Conceptually, these approaches draw on the resource-based view of the firm where firms are seen as bundles of activity-specific competences [62]. These competences can be technical, economic or organisational and constitute the resources that make one firm distinctive from others [63]. These competences are unevenly distributed giving rise to firm heterogeneity and to evolutionary processes of variety creation, replication and selection. This clearly demonstrates SSI's and TIS' conceptual pedigree to heterodox, evolutionary economic thinking and provides the micro-foundations that guide the aggregate behaviour of firms in the system of innovation. The actor set-up in these approaches is not exclusively limited to firms but also includes non-firm organisations such as universities, financial organisations, government agencies, local authorities and so on. However, it is fair to say that especially the SSI approach considers these types of organisations as secondary. This is not to say that they are less important for innovation, rather that they are more indirectly involved with innovation compared to firms. Especially in the case of emergent technologies universities unmistakably play a key role in terms of research and human capital formation. Micro-level conceptualisations of these actors have received far less attention in this literature [64].

The ST-Systems approach is critical of this neglect of other kinds of organisations beyond firms and calls for a broad range of actors to be considered in the system analysis. In lieu of bundles of resources, actors in the system are conceptualised as social groups based on strong coordination principles within the group [32]. Instead of single organisations, ST- Systems takes the inter-organisational community or field as the unit of analysis under the banner of social groups. The disciplining devices to render a social group its distinctive features are shared particular perception, problem-agendas, norms, preferences. In other words, this community is aligned through interrelated rules, i.e. regimes. These rules yield meta-coordination not only within a social group but also between social groups through interpenetration and, thus, provide scope for overlap. On the surface it may appear that SSI, TIS and ST-Systems adopt the same categorisations for the actors in the system (universities, public authorities, consumers, suppliers, banks, etc). It is however important to point out that they depart from quite different micro-foundations for organisational behaviour, originating respectively from a more economical (SSI/TIS) or sociological (ST- Systems) heritage.

This distinction also resonates in the ways that SSI/TIS and ST- Systems deal with the issue of networks and the conceptual pitfalls associated with it. Network analysis in ST-Systems jargon is primarily informed by Actor Network Theory (ANT). It maps relations that are simultaneously material (between things) and 'semiotic' (between concepts) and explores how such networks are formed, stabilised or destroyed. In ST-Systems, Actor Network Theory logic is used to align the different elements of a regime/niche. The distinction between regimes and niche parallels the distinction between so-called ‘hot’ and ‘cold’ situations [65]. In a hot situation everything is contentious and thus results in an unstable ANT whereas in a cold situation the framings are peaceful and institutions (see also below) are stable [26]. Focus is mainly on how relations and linkages emerge whereas ANT can be criticised for lacking explanation as to why networks emerge. The network concept is mainly used in a contextual rather than structural way. SSI and TIS, on the contrary, have a clear grounding in established network theories from economic sociology [66, 67]. It emphasises that economic exchange is embedded in social relations and networks whether it be market relations or corporate hierarchies. This embeddedness can differ greatly across innovation systems. SSI and TIS has paid a lot of attention to the wide range of formal and informal modes of cooperation and interaction among actors. It has successfully demonstrated that networks exist because they integrate knowledge and competences that are widely distributed among firms and other organisations. Especially user-producer linkages and relations in value chains have received a lot of attention as important sources of innovation [see e.g. 57 for the case of fuel cells and hydrogen technology].

Institutions

The way institutions are treated in the SSI, as well as TIS, approach is primarily as signposts for innovators. Institutions provide some sort of stability for firms guiding their behaviour in light of the intrinsic risk connected to innovation activities. Nooteboom [68] conceptualises institutions as 'enabling constraints'. They help and guide behaviour in one direction yet focus it away from alternatives. Therefore institutions are salient factors shaping innovation processes of firms and provide a forceful explanation for the uneven distribution of innovation across countries and regions [37]. However, the territorial varieties of the innovation system approach have been more consistent in treating institutions in a system perspective, drawing attention to institutional complementarities and multi-level institutional couplings [43, 69, 70]. A coherent and consistent approach towards institutional frameworks seems to be somewhat of a weak spot in SSI and TIS analyses.[2] Rather, focus goes to the impact of single institutions analysed in an ad-hoc way [40]. Therefore the influence of institutions on sectoral and technological innovation systems can be regarded as contextual rather than structural. Those institutions that are often pointed out mainly belong to the regulative and cognitive domains: codes, standards and regulation for products and technologies. In comparison normative institutions receive less attention.

The ST-Systems is, in contrast, highly ambitious when it comes to the variety of institutions and institutional frameworks that it takes into consideration. Geels [32] has

[2] The turn towards functions seems to have downturned its analytical attention for the impact of institutions in technological innovation systems [e.g. in 53, 54]

elaborated extensively on the regulative, normative and cognitive dimensions of institutions in connection to ST-systems (see table 1).

INSERT TABLE 1

In this framework, Geels draws extensively on institutional analysis. He suggests that the for short-term analyses, the institutional framework should serve as a relative constant having a strong structuring effect on the behaviour of actors, much in line with the way that institutions are treated in SSI and TIS. However, for longer-term analysis, i.e. in case of transitions from one socio-technical system to another, he argues that attention should be paid to social learning and institutional change. In light of the aforementioned distinction between regimes and niches he argues that existing institutional frameworks create path-dependence and lock-in into existing ST-systems (i.e. regimes). Niches, on the contrary, are locations where it is possible to deviate from rules in the existing regime. The emergence of new paths has been described as a process of mindful deviation [71], where niches provide the locus for this process. This means that *"rules in technological niches are less articulated and clear-cut"* [32, p. 912]. In light of this conceptual comprehensiveness he acknowledges, however, that the complexity of this framework poses considerable challenges to making it operational for empirical research. Historical analyses obviously provide a useful way forward whereas analyses of contemporary institutional change may prove to be more cumbersome.

Knowledge

Knowledge is often seen as the crucial resource for innovation while learning is understood as an indispensable activity or process. All three approaches, SSI, TIS and ST-Systems, agree on this statement as a basic proposition. There are however striking differences between the innovation system approach and the ST-Systems approach respectively, in terms of conceptualising knowledge. Whereas the former highlight the importance of knowledge as a commodity susceptible to economic exchange, the latter pays more attention to knowledge in practice. Knowledge, thus, refers to ability to act rather than to a good [46].

For both SSI and TIS, knowledge is intrinsically tied to technologies. Sectors and technologies differ greatly in terms of knowledge domains and learning processes. The emphasis on technological knowledge does not mean that non-technological knowledge is ignored. Two generic types of knowledge domains receive particular attention. One knowledge domain is defined as *"the specific scientific and technological fields at the base of innovative activities at the base of innovative activities in a sector"* [55]. The other domain concerns, albeit more vaguely defined, applications, users and demand for sectoral products. In similar vein, albeit in the context of national innovation systems, Jensen et al. [50] contrast two forms of knowledge and modes of innovation. The Science, Technology and Innovation (STI) mode is based on the production and use of codified scientific and technical knowledge while the other is an experienced-based mode of learning based on Doing, Using and Interacting (DUI). The authors argue that both modes need to be reconciled through formal processes of R&D that produce explicit and codified knowledge in combination with learning from informal interaction within and between organisations (e.g. through user-producer interaction) resulting in competence-building often with tacit elements. In empirical studies, technological knowledge and R&D have received most attention, partly because it can be measured in a relatively straightforward manner through R&D expenses and patents. Within the innovation system literature there is also a clear bias for economically useful knowledge. This is illustrated by the various dimensions that are used to analyse the relevance of knowledge for explaining innovative activities [29]. Knowledge may have different degrees of accessibility, understood as opportunities for gaining knowledge, cumulativeness, understood as the degree to which the generation of new knowledge builds upon current knowledge and appropiability, understood as the possibility of protecting knowledge from imitation and of reaping profits from innovative activities (e.g. through patents).

The ST-Systems approach acknowledges the importance of and need for the creation of technological knowledge for innovation much in line with the SSI and TIS approaches. In addition, it suggests a more elaborated understanding of the user side of technology that goes beyond passive knowledge diffusion. *"Users also have to integrate new technologies in their practices, organisations and routines, something which involves learning, and adjustments. New technologies have to be 'tamed' to fit in concrete routines and application contexts (including existing artefacts). Such domestication involves symbolic work, practical work, in which users integrate the artefact in their user practices, and cognitive work, which includes learning about the artefact"* [32, p. 902]. Innovation can thus be understood as an outcome of the ongoing alignment of technology and the user environment in a co-evolutionary manner where adaptation takes place on either side. This caters for a more process-oriented understanding of the role of knowledge creation, exchange and use. It can therefore be argues that social learning has received more attention in the ST-Systems approach than in the SSI and TIS approaches. Partly this has to do with the stronger linkages to sociological theories, compared to the more pronounced economical orientation of SSI and TIS. According to Geels [32] social learning refers to the reproduction or transformation of cognitive, normative and regulative rules through imitation or through the exchange of experiences. This manifested through adjustments of user representations, routines or shared expectation. The relative bias in favour of technological learning (SSI and TIS) or social learning (ST-Systems) clearly reverberates in the degree of novelty that is studied (see below).

Dynamics

The three approaches differ substantially in terms of analysing dynamics and change. The basic rationale for change in SSI is based on evolutionary processes –mainly oriented to incremental innovation. TIS have its focus on (particular) emergent technologies that have not yet achieved a break-through. ST-Systems is first and foremost geared to analysing change – especially from a broad societal perspective.

In the SSI framework, variety creation takes place at the level of products, technologies, firms, and institutions and is caused by the heterogeneity among actors. Systems can evolve as a consequence of the entrance of new agents into the system. Especially new actor entry (e.g. spin-off firms) is considered as particularly important for the dynamics, processes of change and transformation of a sector. Selection processes, in turn, reduce this heterogeneity and drive out inefficient or less progressive firms. Market plays an important role for selection even though the SSI literature also opens up for the possibilities of non-market selection (e.g. in the cases of the military and the health system). Changes in sectoral systems are thus the result of co-evolutionary processes of their various elements, involving knowledge, technology, actors, and institutions. These processes are often path-dependent and, through increasing returns and irreversibilities, susceptible for lock-in [55]. A result of this evolutionary perspective is that the approach is mainly geared towards incremental change and step-wise improvement. Moreover recent contributions in the field of TIS have criticised the SSI approach for employing a snap-shot perspective that falls short of explaining the emergence of new sectors and technologies.

According to Hekkert, Suurs, et al. [53] there is an exclusive focus on analysing the social and institutional structures of different innovation systems. *"Since technological change is a dynamic process, which requires a transformation of the innovation system in which changes take place, a dynamic innovation system approach is needed to understand and better be able to guide its direction"* [53, p. 414]. To remedy this shortcoming they suggest paying more attention to the various functions and activities that take place in an innovation system. In doing so, they seek to outline a more dynamic innovation system framework. Based on empirical studies they suggest the following set of functions to be applied when mapping key activities, and to describe and explain shifts in technology specific innovation systems. (1) Entrepreneurial activities, (2) knowledge development, (3) knowledge diffusion through networks, (4) guidance of search, (5) market formation, (6) resource mobilisation, (7) creation of legitimacy, counteract resistance to change. Hekkert, Suurs et al [53] imported ‘dynamic’ notions from the technology systems approach [30], and applied them to the interactions and momentum of innovation system’s functions. The authors propose that, since functions influence each other, a virtuous cycle can be created within an innovation system. In this way, systems behave non-linearly with several function interactions that create a momentum (called motors of change). This momentum will ultimately have a positive effect on the overall efficiency of the system at the time it stimulates structural change for systemic innovation. This inherently dynamic framework seems to be part of a wider tendency in the innovation system literature to focus not only on changes in the system, but also to changes of the system [33, 54].[3] It needs to be noted, though, that the functions approach to innovation systems may have substituted, rather than complemented, the emphasis on functions for social and institutional structures. Derived of their social and institutional dimensions this turn runs the risk of treating innovation systems in a mechanistic way.

The ST-Systems framework is primarily geared to analysing technological transitions whereas the innovation system approach has difficulties doing so by means of its focus on intra-system drivers, interactions and dynamics. Through its distinct use of the niche and regime concepts, the approach has proven to constitute a highly appropriate framework to understand and explain large-scale and discontinuous changes in socio-technological systems. In ST-Systems, technological transitions can take a long period of time – often more than one generation. During a transition, long periods of relative

[3] Bergek et al. [54, p 426] presents a comparative exercise of the nine known attempts to identify functions for assessing the dynamics of an innovation system.

stability and optimisation are followed by relatively short periods of structural change. In this process a paradigm shift takes place and existing structures are broken down and new ones emerge [19]. The multi-level perspective is used in ST-Systems to explain such a dynamic process of change (transition), albeit *"it is not seen as an ontological description of reality but as an analytical and heuristic framework"* [31, p. 1273]. In particular, this perspective explains processes of variation and selection (niches), selection and retention (niches), and processes of reconfiguration and radical change (regime shifts). The macro level (landscape) consists in slow changing external factors. The meso level of socio-technical regimes refer to stability of existing technological developments. The micro level deals with the generation and development of radical innovations [31]. Various empirical studies bear evidence to this [e.g. 72, 73-75]. These empirical studies are characterised by long time frames and historical analysis providing convincing accounts of substantial change processes. Markard and Truffer [26] remain however critical of the near exclusive niche-based explanations for technological transitions. Secondly, as mentioned earlier, the bias towards sweeping historical accounts comes at the cost of individual actor behaviour and strategy making.

Conclusions

This paper provides a systematic comparative analysis of three influential analytical framework that are often used to investigate drivers and barriers for innovation and ultimately, improved competitiveness or sustainability at the level of sectoral systems (SSI), technological systems (TIS) or societal functions (ST-systems). The three approaches clearly address different rationales for innovation and technological change.

In the SSI framework and the pioneering work of TIS, innovation had a predominantly economically oriented goal, i.e. to improve competitiveness and to induce economic growth. Later work on TIS, as well as a major share of the studies of ST-systems, has focused its analyses to a large extent on sustainable technology development and ‘green’ transitions in society, particularly in the areas of energy and mobility. Following the notion of ecological modernisation, efforts to create a win-win situation between economic competitiveness and environmental sustainability would thus profit from a lessons and insights from all three bodies of literature. However, this paper reveals that substantial conceptual differences (as well as commonalities) exist between the respective frameworks that resist a problem-free synthesis. Table 2 provides a systematic overview of our main findings. We shall conclude this paper by highlighting the main differences between the three frameworks and raise suggestions for complimentarily.

INSERT TABLE 2

With regard to the system boundaries, the SSI framework is particularly helpful when the system components (firms and institutions) are given and relatively stable. Standardised statistics following e.g. NACE nomenclature allow for rigorous analysis of determinants and effects of innovation within and between sectors across time and territories. A commonly used source is the community innovation survey (CIS). This is the case of current work on innovation performance of nine European sectors (commissioned by the European Comission), which is using the SSI approach[4]. TIS and ST-Systems are more concerned with technologies and socio-technical systems that are in a state of emergence

[4] Europe INNOVA Sectoral Innovation Watch Initiative

and/or transformation. Studies of TIS are therefore often forced to construct their own databases as the object of study has not been included in standardised surveys. The focus on firm behaviour facilitates the use of quantitative analysis. With regard to its system definition the ST-Systems framework is most inclusive vis-a-vis the components of the system. This avoids a firm-centric bias for explaining innovation and technological change, found in SSI and TIS, but makes it more difficult to employ quantitative methods to analyse system dynamics. In light of the heterogeneity of the actors and institutions that are considered, most empirical analyses of ST-Systems draw on historical case study analyses. One possible area for complimentarily could therefore consist of the narrow and therefore easily quantifiable system definition, in terms of actors and institutions, found in SSI and TIS frameworks versus the homogeneous, broad and open-ended system definition found in ST-Systems which primarily draw on case narratives.

With regard to the actors, networks and institutions found in the systems, another area of complimentarily can be mentioned between SSI and TIS on the one hand and ST-Systems on the other. Through their focus on firm behaviour the former frameworks have the potential to connect a micro-level theory of firm behaviour with system dynamics. This yields potentially important insights on the level of individual actors' strategies and behaviour, including networking behaviour and impact. ST-Systems, on the other has its strength in the broad field of actors that are implied in the system but lacks a micro-foundation for actor behaviour. Moreover, the use of network analysis is primarily contextual. With regard to institutions, however, the opposite situation occurs. Here the

ST-Systems framework allows for a greater level of conceptual sophistication than the SSI and TIS frameworks.

Finally there is a clear are of complimentarily with regard to the ways knowledge and system dynamics are conceptualised in the respective frameworks. Whereas SSI and TIS are primarily geared to explaining change *in the system* the ST-System framework is more concerned with change *of the system*. An analytical framework able to assess innovation dynamics for both competitiveness and sustainability would require the conceptual tools to do both.

It has not been the objective of this paper to arrive at an integrated framework based on SSI, TIS and ST-Systems to analyse innovation dynamics serving the twofold rationale of competitiveness and sustainability. The review shows that respective frameworks (in particular SST and TIS on the one hand and ST-Systems on the other) are firmly grounded in their heterodox economics and sociologies of science and technology vantage points. However, the contribution of this review has been to specify on which dimensions further theoretical (and empirical) work is needed to bring respective fields closer together. At present, epistemological fault lines are primarily running with regard to the system boundaries and definitions, the connection with micro-level theories and explanations and the conceptualisation of change. Future research on these dimensions will hopefully bring these strands closer to each other, thus catering for a more integrated framework to investigate drivers, barriers and impact of innovation in cleaner technologies for sustainability and competitiveness.

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Vitae

Dr. Lars Coenen

Lars Coenen is assistant professor in Economic Geography at CIRCLE with a particular interest in the geographies of innovation. His PhD thesis (2006) entitled 'Faraway, so Close! The Changing Geographies of Regional Innovation', contains various comparative studies across different industries and regions to investigate how local and global knowledge is combined in a productive nexus of learning processes at the regional level. At present his research focus is converging around the notions of regional innovation systems and the spatial dynamics of socio-technical transitions in relation to sustainable technologies. In his analyses Lars seeks to compare the emergence and diffusion of radical innovation in areas such as bio-fuels and passive housing across different territorial contexts. In 2008-2009 he also worked for the Dutch Knowledge Centre for Transition at TNO, the Netherlands Organisation for Applied Scientific Research.

Dr. Fernando J. Diaz Lopez

Fernando J. Diaz Lopez works at the Netherlands Organisation for Applied Scientific Research TNO- Built Environment and Geosciences (Innovation and Environment Group) as a researcher and advisor on sustainable innovation. He holds a B.Sc. in Chemical Engineering, a MPhil in Economics and Management of Innovation, and a PhD in Human Geography from the University of East Anglia (UK). His PhD thesis developed methods and indicators for measuring eco-innovations strategies in firms, which were tested in the chemical industry. Prior to his research/consultancy career, Dr Diaz Lopez held an engineering position as an environmental manager in the chemical industry. At present his research focuses on eco-innovation strategies and policies, future scenarios for emerging eco-innovations and cleaner technologies (especially in chemicals, textiles, food, biotechnology and construction), (sectoral, regional and technological) innovation systems for the transfer of eco-innovations, and system approaches for sustainable consumption and production.

Tables and Figures

Table 1 Examples of rules in different regimes

	Formal/regulative	Normative	Cognitive
Technological and product regimes (research, development, production)	Technical standards, product specifications (e.g. emissions, weight), functional requirements (articulated by customers or marketing departments), accounting rules to establish profitability for R&D projects (Christensen, 1997), expected capital return rate for investments, R&D subsidies.	Companies own sense of itself (what company are we? what business are we in?), authority structures in technical communities or firms, testing procedures.	Search heuristics, routines, exemplars (Dosi, 1982; Nelson and Winter, 1982), guiding principles, (Elzen et al., 1990), expectations (Van Lente, 1993; Van Lente and Rip, 1998), technological guideposts (Sahal, 1985), technical problem agenda, presumptive anomalies (Constant, 1980), problem solving strategies, technical recipes, 'user representations'(Akrich, 1995), interpretative flexibility and technological frame (Bijker, 1995), classifications (Bowker and Star, 2000)
Science regimes	Formal research programmes (in research groups, governments), professional boundaries, rules for government subsidies.	Review procedures for publications, norms for citations, academic values and norms (Merton, 1973)	Paradigms (Khun, 1962), exemplars, criteria and methods of knowledge production.
Policy regimes	Administrative regulations and procedures which structure the legislative process, formal regulations of technology (e.g. safety standards, emissions norms), subsidy programs.	Policy goals, interaction patterns between industry and government (e.g. corporatism), institutional commitment to existing systems (Walker, 2000), role perceptions of government.	Ideas about the effectiveness of instruments, guiding principles (e.g. liberalisation), problem-agendas.
Socio-cultural regimes (societal groups, media)	Rules which structure the Spreads of information production of cultural symbols (e.g. media laws)	Cultural values in society or sectors, ways in which users interact with firms (Lundvall, 1988)	Symbolic meanings of technologies, ideas about impacts, cultural categories.
Users, markets and distribution networks	Construction of markets through laws and rules (Callon, 1998, 1999; Green, 1992; Spar, 2001); property rights, product quality laws, liability rules, market subsidies, tax credits to users, competitions rules, safety requirements.	Interlocking role relationships between users and firms, mutual perceptions and expectations (White, 1981, 1988; Swedberg, 1994)	User practices, user preferences, user competencies, interpretation of functionalities of technologies, beliefs about the efficiency of (free) markets, perception of what 'the market' wants (i.e. selection criteria, user preference)

Source: [32] p. 906

Table 2. Summary of systemic comparison of SSI, TIS and ST-Systems

	System Boundaries	Actors	Networks	Institutions	Knowledge	Dynamics
Sectoral Innovation Systems	a. Based on a product or product group (e.g. automobiles), standardised through NACE b. Involves multiple technologies c. Not geographically bounded	a. Heterogeneous but mainly firm focused b. Micro-foundation: heterodox economic theories (for firms) c. Role of universities and state is 'firm-centric'	a. Major focus on network analysis (qualitative and quantitative) b. Analysis is informed by socio-economic network theories (organisational studies, Social Network Analysis)	a. Institutions are primarily conceptualised as signposts for innovation (facilitating risk-taking) b. Relatively narrow institutional analysis focused on (sector-specific) regulative and cognitive institutions c. Institutions are often analysed as stand-alone (emphasis is contextual rather than structural)	a. Emphasis on knowledge as commodity (elaborate conceptualisation) b. Emphasis on technological innovation and R&D c. Focus on incremental innovation	a. Change is mainly conceptualised as inc co-evolution b. Framework as suc (snap-shot) "
Technological Innovation Systems	a. Based on technological domain b. May involve different sectors c. Not geographically bounded	a. Heterogeneous but mainly firm focused b. Micro-foundation: heterodox economic theories (for firms) c. Role of universities and state is more independent but not explicitly conceptualised on micro-level	a. Some focus on network analysis, decreased attention for network aspects in Functions approach b. Analysis is informed by socio-economic network theories (organisational studies, SNA)	a. Institutions are primarily conceptualised as signposts for innovation (facilitating risk-taking). Functions Approach pays little attention to institutional analysis. b. Relatively narrow institutional analysis focused on technology-specific) regulative and cognitive institutions c. Institutions are often analysed as stand-alone (emphasis is contextual rather than structural)	a. Emphasis on knowledge as commodity (elaborate conceptualisation) b. Emphasis on technological innovation and R&D c. Focus on incremental and radical innovation	a. Change is concep radical and incremen evolution b. Especially the fun approach is focused processes (dynamic)
Socio-Technical Systems + Transitions	a. Based on societal functions (e.g. mobility) b. Involves multiple industrial sectors & technologies c. Often geographically bounded (mainly nationally)	a. Heterogeneous involving broad spectrum of societal actors b. No explicit theoretical micro-foundations for actor behaviour, preference for sociological conceptualisations c. Role of societal actors is considered as autonomous	a. Networks are implied as basic organisational structure between actors but little use of explicit network theories (emphasis is contextual rather than structural) b. Analysis is primarily informed by Actor Network Theory	a. Institutions are primarily conceptualised as signposts for stability, pathe-dependence and lock-in (due to emphasis on niche activities) b. In principle, broad approach to institutions, encompassing regulative, normative and cognitive institutions c. Regime is analysed from aggregated level, niche from stand-alone level (institutions are fluid / emergent)	a. Emphasis on learning (knowing in practice) b. Focus on technological and non-technological innovation c. Emphasis on radical innovation but also acknowledgement of need for incremental innovation	a. Change is concept transitions (niche & r metaphors) b. Framework as suc dynamic (historical a

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