A literature review on

Energy Innovation Systems

Structure of an emerging scholarly field and its future research directions

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1 Introduction and overview

Energy related innovation is receiving increasing attention worldwide. This may be explained by recent developments in the policy discourse in many countries. The threat of global climate change, projections of scarcities of fossil sources (peak oil), and major disasters like Fukushima have put the need to radically rethinking and rebuilding energy sectors very high on the political agenda of many countries. National energy policies in countries like Germany or Switzerland have been formulated to move out of nuclear power and to embark on an energy sector transition that builds on renewable energy technologies and energy efficiency. Partly as a consequence of these developments, a number of small scale niche technologies that were considered “hopeful monstrosities” twenty years ago, have meanwhile developed into veritable industries. Photovoltaic electricity generation and wind power are two cases in point. But also irrespective of environmental public policy priorities, energy sector structures will experience strong pressures for transformation due to new information and communication technologies, which allow for radically different system layouts and open up perspectives for more distributed generation and smarter grid configurations. Finally, also the changing geography of energy innovation has to be reconsidered. Emerging and developing countries are becoming increasingly important players in the quest of future energy systems. Many are considering options for leapfrogging towards higher shares of renewables, circumventing problems of greenhouse gas emissions and nuclear waste associated with conventional technologies.

Based on this state of affairs, the present report builds on an understanding that transformations in the energy sector are likely to be highly complex and will run over several decades. Technological and social aspects have to be considered in their systemic interplay. A literature that has addressed innovation in a socio-technical systems perspective has emerged over the past thirty years under the label of “innovation systems”. The present report takes stock of innovation systems research in its application to energy related problems. It thus aims at providing an overview of current trends and challenges in energy related innovation systems research. It focuses on major conceptual, methodological and empirical developments and identifies areas for promising future research.

In the following section, we will provide an overview of energy research that applies innovation systems concepts. Among the different sub-orientations of national (NIS), regional (RIS), sectoral (SIS) and technological (TIS) innovation systems, the TIS tradition has been by far the most productive in the energy field. Scholars using the other approaches have started to consider energy problems as a legitimate field of application but have not yet developed coherent research programs in this field. We will review that major research lines and work out similarities and complementarities among these traditions. In the third section, we will elaborate in some detail the current conceptual, methodological and empirical challenges that have been identified in the TIS literature. Section four provides a detailed and encompassing overview over the most recent academic literature on energy innovation systems. Section five concludes by discussing the prospects of an emerging “energy innovation systems” agenda and proposes some avenues for future research.

2 Energy innovation system research: different perspectives

The origins of the innovation systems concepts can be traced back to the late eighties, when the national system of innovation concept was formulated (Lundvall, 1992). It was developed in order to provide a conceptual framework for technology and innovation policy for national (and international) policy makers, emphasizing the role of institutional framework conditions and the evolutionary nature of innovation processes. The innovation system perspective was explicitly conceived as a counterpoint to policy advice stemming from the neo-classical economics tradition, which was perceived as providing no explanation for the major economic challenges of the 1980ies, like the rapid raise of Japan as a technology leader (Sharif 2006). The core assumption was that nationally specific institutional arrangements between science, policy and industry explained differences in innovation success among different countries (especially the technology leaders US, Germany and Japan). Particular institutional arrangement which were analyzed encompass the science-industry interface, the availability of venture capital structures, specific industrial policy programs or a broader cultural context supporting innovativeness. The totality of these institutional arrangements was understood as constituting a more or less coherent "national system" supporting (or hindering) the generation of novelty. Besides the structural components, emphasis was also put on processes like learning (learning by doing, by using, by interacting, etc.) and exchanges among different kinds of actors (e.g. user-producer relationships, science-industry co-operations, industrial networks). These concepts were applied to core industries in the leading industrialized countries (like the automobile industry, consumer electronics, the machine tool industry or pharmaceuticals). Geographically this literature had therefore originally a strong focus on Japan, the US and Germany.

Later work on innovation systems accepted most of these initially set assumptions. Basically, all newer proposals acknowledge the importance of analyzing the systemic interplay between actors, networks and institutions and also they extend and differentiate the process concepts. However, the alternative concept variants called SIS, RIS or TIS started with a strong critique of the original NIS literature: the major shortcoming was seen in the *a priori* delimitation of systems along national boundaries. Essentially, RIS, SIS and TIS claim that systemic coherences are often following regional, sectoral or technological logics which may crisscross national boundaries. An exclusive focus on innovation within specific national boundaries either risks missing out on important boundary crossing structures and processes or then averages out over a too broad and incoherent assemblage of such elements. Therefore the set of the four innovation system approaches is best characterized as providing different (and probably quite complementary) vantage points for analyzing similar kinds of objects (namely the systemic interplay between actors, networks and institutions) rather than competing theories.

Energy or other cleantech sectors did not feature prominently as an empirical application field in the early NIS writings. This has to do with their taken for granted character, low innovation intensity of public services sector and a rather low level of attention that was paid to global environmental problems and energy security in the early eighties (being a sort of interlude in between the oil crises of the 1970ies and the emerging global climate change and sustainability debate unfolding in the 1090ies). A notable exception was a paper from Chris Freeman (1996) where he ventured into the possibility that cleantech could become the basis for a 6^{th} Kondratieff cycle leading to a new wave of technological innovation and widespread prosperity. However, this very thought-provoking contribution seemed not to leave a strong mark on the quickly enfolding mainstream of the innovation systems literature and as a consequence it did not provoke a lot of resonance in the NIS, RIS and SIS communities.

Technological innovation and sectoral change processes driven by environmental concerns were more prominently researched in an emerging sub-community within the field of innovation studies. This new field has become known under the label of "sustainability transitions studies" (see Markard et al. 2012; van den Bergh et al 2011). Transition studies are concerned with historical transformation processes of socio-technical systems such as energy supply or transportation (Geels et al., 2012). Within the sustainability transitions community, innovation systems concepts feature prominently, however mostly in the variant of technological innovation systems (TIS). In the TIS tradition quite an impressive range of empirical accounts of emerging industries in the energy and other clean-tech sectors has been developed (e.g. Jacobsson and Johnson, 2000; Jacobsson and Bergek, 2004; Negro et al., 2007; Markard et al. 2009; Dewald and Truffer, 2011). The other variants (NIS, RIS and SIS) have been rather absent from this discourse.

As a consequence, we will split the review on energy innovation systems research in two parts. In the following section, we will give an overview of energy related innovation systems research referring explicitly to the RIS, NIS or SIS perspective. The later sections will then exclusively deal with the development and key findings gained within the TIS tradition. Despite the main focus on TIS research, we argue that there still is a high degree of conceptual overlap and the specific innovation system approaches can be seen as providing largely complementary evidence. We will return to this point in section 2.4.

2.1 Energy research in the NIS, RIS and SIS perspective

As energy and cleantech are rather marginal empirical application fields within the three perspectives NIS, SIS and RIS, we adopted an inductive approach to analyze the literature. An extensive search in the Scopus data base[1] provided 194 academic papers that were explicitly mentioning the term "innovation system" and addressing some energy related empirical problem. Among these publications, however only 35 did not draw on the technological innovation system concept. This general result corroborates the impression that NIS, SIS and RIS approaches have not yet identified energy as a strong and coherent field for empirical investigation. A large share of these 35 papers relates to specific renewable energy technologies like bio-energy, wind, photovoltaic, fuel cells or energy efficiency in the building sector (16). About the same number of papers (14) addresses generic topics such as renewable energy in general or even clean-tech. A couple of papers either focus on specific policies (e.g. European emission trading system, ETS) or non-renewable energies (nuclear power or carbon capture and storage technologies, CCS). Over time, we see a slight recent increase: 19 out of the 35 publications were published in the last two and a half years (2010-2012).

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[1] Search string: TITLE-ABS-KEY("innovation system*" OR "system of innovation" OR "regional innovation system*" OR "regional system of innovation" OR "national innovation system*" OR "national system of innovation" OR "sectoral system*" OR "sectoral innovation system" OR "sectoral system of innovation" OR "regional innovation system*" OR "regional system of innovation" OR "technological innovation system*" OR "technological system of innovation") AND TITLE-ABS-KEY(photovoltaic* OR "PV" OR wind OR "wind power" OR solar OR biofuel* OR "bioethanol" OR "micro-CHP" OR "CHP" OR "combined heat and power" OR "carbon capture and storage" OR "CCS" OR "energy system" OR "electricity system" OR "energy system" OR "smart grid" OR hydrogen OR "fuel cell*" OR "renewable energy" OR "wind energy" OR "biomass" OR "biogas" OR "energy" OR "sustainable energy" OR "bioenergy" OR "low carbon" OR hydro OR "hydro power" OR nuclear OR coal OR "coal power" OR "natural gas" OR "biomass gasification" OR "gas power" OR "natural gas")

However, we have to take into account that quite an important share (about 10%) of the database entries are conference proceedings and not publications in peer reviewed journals, which reinforces the overall impression of energy being not yet a strong field of application for these approaches.

The majority of the selected papers (17) subscribe to a NIS perspective. Some discuss the impact of national regulatory pressures to develop renewable energies (Gebhardt 2002), especially under the conditions of being implemented in an infrastructure sector (Walz 2007). An important question is here whether strong environmental regulations lead to longer term technology leadership of a country as suggested by the famous Porter and van der Linde (1995) hypothesis and what intermediating role accrues to specific NIS structures in this regard (Constantini and Crespi 2008). More structure oriented approaches focus, for instance, on the role of the vocational education system for the success of specific technologies (e.g. for fuel cells see Hung and Chang 2011) or the role of specific organizations like the applied technology research centre system VTT in Finland (Kutinlahti and Hyytinen 2002). Others show how specific national institutional arrangements explain the success of certain energy innovations (like bioethanol in Brazil, see Furtado et al. 2011) or how specific institutions like standards are based on specific features of the NIS (De Souza and Hasenclever 2011). NIS approaches are often applied to the analysis innovations in emerging economies and developing countries. Here, issues like technology transfer or leapfrogging are addressed (e.g. Fu and Zhang 2011). A particularly interesting argument is elaborated by Provance et al. (2011) who analyze the role of specific NIS structures for successfully developing new business models for micro-generation. By this they propose to connect system structures with the strategies of individual firms.

Among the papers that explicitly refer to the SIS framework (10) there are quite a few which define the term sector rather synonymously with specific technologies (like photovoltaics, wind or bioethanol). The difference between these approaches and TIS studies seems not all too clear-cut, especially for those cases that deal with emerging industries (see for instance Kristinsson and Rao 2008; Marinova and Balaguer 2009; Kedron and Sharmistha 2009; Vidican et al. 2008). Marinova and Balaguer (2009) are particularly interesting as they adopt a comparative framework for analyzing PV industry formation in Germany, Japan and Australia and using differences in the respective NIS structures as explanatory variables. More specific sectoral approaches ask for the implications of external factors impacting the energy (or housing) sectors on radical innovations. Some authors conclude that SIS tend to strongly favor incremental innovations (Kubeczko et al. 2006 or Beerepoot and Beerepoot 2007) whereas others see positive impacts on the promotion of renewable energies depending on the kind of external stimulus (e.g. for the case of the EU ETS, see Rogge and Hoffmann 2010 or for oil prices see Cheon and Urpelainen 2012).[2]

The RIS perspective (5 papers) mostly confirms that regional innovation systems structures and innovative clusters actually represent very conducive backgrounds for energy innovations (Cooke 2010; specifically for fuel cells see Madsen and Andersen 2010). Some of these studies emphasize the

2 There is likely a much broader discourse on conditions for innovation in the energy sectors that was not captured by our search string. Namely, the impact of specific institutional reforms on the inclination of electric utilities to move into radical innovations or not would be a case (see for instance Markard and Truffer, 2006). This larger literature was not included as it does not explicitly refer to an innovation system framework.

importance of specific institutional structures like regional technology innovation centers for supporting innovations in the energy sector (Goddard et al. 2012).

Overall, we can conclude that a small, but recently growing stream of innovation system research on energy outside of the technological innovation system tradition exists. The literature is quite diverse though and not well developed for providing a coherent perspective on energy innovations. Also, as all innovation systems approaches focus on a diversity of actors, their networks and institutional arrangements, the different perspectives often come to very similar conclusions and it is hard to tell where the added value of each of the approaches lies. This is especially true for those examples which focus on specific technologies (like photovoltaics, wind, fuel cells, etc.). Starting from this assessment, we will now present the – more vibrantly developing – TIS approach to energy innovation in some more detail. In section 2.4 we will come back to the question how the different IS perspectives might complement each other.

2.2 Development of the TIS perspective

Research on technological innovation systems (TIS) has emerged as major line of inquiry in the broader field of transition studies (Markard et al., 2012). The TIS framework is well suited to study emerging industries that develop out of radically new technologies and the institutional and organizational changes that have to go hand in hand with technology development. Below, we briefly review the emergence of the framework and its main lessons.

The TIS concept can be traced back to the seminal paper of Carlsson and Stankiewicz (1991) that highlighted the systemic interplay of firms and other actors under a particular institutional infrastructure as the essential driver behind the generation, diffusion and utilization of technological innovations. The authors relate their concept primarily to Dahmén's work on development blocks which are constantly evolving systems centered on a generic technology (Dahmen, 1988; Enflo et al., 2008). There are also linkages to the concepts of national innovation systems (Freeman, 1988; Nelson, 1988), regional and sectoral innovation systems (Cooke et al., 1997; Malerba, 2002) and the innovation systems approach formulated by scholars at Lund University (e.g. Edquist, 1997).

In the 1990s, TIS research focused on a variety of systems, which were delineated in various ways. Some focused on a specific field of knowledge, such as microwave engineering, a particular material technology or biocompatible materials. Others were delineated by a product (e.g. CNC machine tools) or product group (e.g. factory automation) whereas yet others had a sectoral focus, such as electronics industry or biomedical industry. Some of these systems were mature whereas others were in an early phase of development.

The framework has seen several conceptual refinements (Carlsson et al., 2002), one of the most influential being the identification of key processes, so-called functions (see table 1), which need to run smoothly for the system to perform well (Johnson, 2001; Johnson and Jacobsson, 2001; Jacobsson and Bergek, 2004; Hekkert et al., 2007; Bergek et al., 2008a). Other conceptual contributions have directed attention to the complementarities of TIS and the multi-level perspective (Markard and Truffer, 2008b; Coenen and Diaz-Lopez, 2010), to prospective technology analyses (Markard et al., 2009), to the interaction of different technological innovation systems (Sanden and Hillman, 2011; Wirth and Markard, 2011) and to processes of system building (Hellsmark and Jacobsson, 2009; Musiolik and Markard, 2011; Musiolik et al, 2012; Dewald and Truffer, 2011).

Table 1: Key processes in technological innovation system build-up

Key process	Definition	Indicators
Knowledge creation and diffusion	Activities that create new knowledge, e.g. learning by searching, learning by doing; activities that lead to exchange of information among actors, learning by interacting and learning by using in networks	R&D projects, no. of involved actors, no. of workshops and conferences, network size and intensity, activities of industry associations, websites, conferences, linkages among key stakeholders
Influence on the direction of the search	Activities that positively affect the visibility of requirements of actors (users) and that have an influence on further investments in the technology	Targets set by the government, changes in regulatory frameworks, no. of press articles that raise expectations, visions and beliefs in growth potential
Entrepreneurial experimentation	Emergence and decline of active entrepreneurs as a prime indication of the performance of an innovation system, concrete activities to appropriate basic knowledge, to generate and realize business opportunities	No. of new entrants, no. of diversification activities of incumbents, no. of experiments
Market formation	Activities that contribute to the creation of demand or the provision of protected space for the new technology, e.g. construction of market segments	No. of niche markets, specific tax regimes and regulations, environmental standards
Creation of legitimacy	Activities that counteract resistance to change or improve taken-for-grantedness of new technologies	Rise and growth of interest groups and their lobbying activities
Resource mobilization	Activities related to the mobilization and allocation of basic inputs such as financial, material or human capital	Availability of competence/human capital, financial capital, complementary assets for key actors
Development of positive externalities	Outcomes of investments or of activities that cannot be fully appropriated by the investor, free resources that increase with number of entrants, emerge through firm co-location in TIS	Emergence of pooled labor markets, intermediate goods and service providers, information flows and knowledge spill-overs

Source: Compiled from (Bergek, Jacobsson, Carlsson, Lindmark, et al. 2008a; Hekkert, Suurs, Negro, Kuhlmann, et al. 2007; Musiolik and Markard 2011)

From their beginning, many analyses of technological innovation systems were intended to inform policy making (Carlsson et al., 2002) which is why the identification of drivers and barriers to innovation is a typical task performed in TIS studies (Carlsson and Jacobsson, 1997; Bergek and Jacobsson, 2003; Jacobsson and Bergek, 2004; Jacobsson and Lauber, 2006; Negro and Hekkert, 2008). In fact, one of the major contributions of the innovation systems perspective is that it has left behind and replaced the narrow concept of market failures by a broader set of system weaknesses (or system failures), expressed either in structural and/or functional terms (Carlsson and Jacobsson, 1997; Bergek et al., 2008a; Jacobsson and Johnson, 2000; Klein Woolthuis et al., 2005; Kuhlmann et al., 2010; Weber and Rohracher, 2012). Combined with the aforementioned shift towards technology-specific innovation systems this has paved the way for suggesting technology-specific policies on the basis of TIS analyses (Carlsson and Jacobsson, 1997; Jacobsson and Bergek, 2004; Jacobsson and Bergek, 2011; Sandén and Azar, 2005; Azar and Sandén 2011).

Energy has always been a very prominent topic both in the broader field of sustainability transitions and in research on technological innovation systems. One of the early major contributions is Jacobsson and Johnson (2000), in which the authors explore the development of renewable energy technologies and discuss barriers to their diffusion on the basis of an innovation systems perspective.

Many influential papers have followed since then, including studies on renewable energy technologies in general (e.g. Jacobsson and Johnson, 2000; Johnson and Jacobsson, 2001) as well as more specific analyses on photovoltaics (e.g. Jacobsson et al., 2004; Dewald and Truffer, 2011; Dewald and Truffer 2012), wind energy (e.g. Bergek and Jacobsson, 2003; Markard and Petersen, 2009), biomass (e.g. Jacobsson, 2008; Negro et al., 2007; Negro and Hekkert, 2008; Wirth and Markard, 2011; Markard et al. 2009), biofuels (e.g. Suurs and Hekkert, 2009 and Hellsmark, 2010), carbon capture and storage (van Alphen 2010) or fuel cells (e.g. Markard and Truffer, 2008a; Musiolik and Markard, 2011; Konrad et al., 2012). This shift towards focusing on energy related innovations was accompanied by a greater attention to innovations in an early stage of development with a potential to challenge established socio-technical systems. In other words, over the years the analytical interest in TIS research shifted from general technological innovations contributing to the economic growth of countries to new (energy) technologies as nuclei for fundamental socio-technical transitions (see figure 1).

A typical characteristic of many of these later studies is that a selected energy innovation is studied in the context of a particular country, given the national regulatory and industry structures. Some researchers have also compared the development between different countries but this has rather remained the exception (e.g. Bergek and Jacobsson, 2003; Jacobsson and Bergek, 2004, Hellsmark, 2010; van Alphen, 2010). Only recently, scholars have begun to go beyond the initial national study setting with regional and global analysis of the structures of technological innovation systems (Coenen et al., 2012; Dewald and Truffer, 2012; Binz, et al. 2012).

Regarding their geographical focus, energy related TIS studies have mostly developed by European research groups from Sweden (Chalmers), the Netherlands (Utrecht), Switzerland (Eawag) or Austria (ARC and IFZ). More recently, the concepts have been taken up in emerging economies like China or Brazil. In the US, a concept named “energy technology innovation systems” (Gallagher et al. 2012) was presented that builds (although selectively) on some of the larger TIS literature.

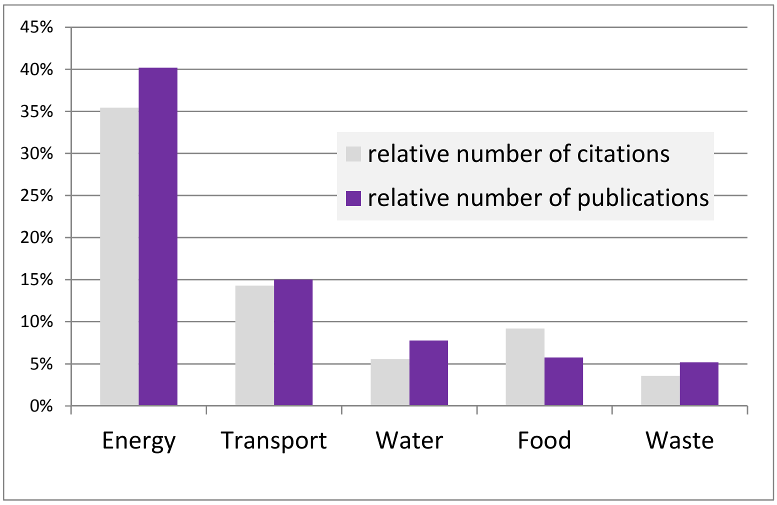

Figure 1: Relative importance of energy as a topic in the broader field of sustainability transition studies (Markard et al., 2012)

2.3 Major lessons from TIS studies on new energy technologies

TIS studies on emerging energy technologies have generated a number of insights, which are key to understand the dynamics we observe in the field and to derive policies to foster energy innovation systems. Some of these insights also relate to the broader characteristics of energy sectors as being constituted by well-established socio-technical regimes and an infrastructure that is capital intensive, durable and highly systemic (Markard 2011). This implies that there is a high degree of inertia due to strong vested interests (economic and political) and a high technical and institutional interdependence of system components. As a matter of fact, the general type of innovation is incremental and radical socio-technological change is rather the exception.

- **Lock-in:** New energy technologies that deviate from established structures (e.g. distributed electricity generation) have a hard time to develop because the energy sector is very much locked into established technologies; existing institutional, organizational and political structures support the established technologies; in the electricity and gas sector, lock-ins are aggravated due to the capital intensity and durability of existing technologies and network infrastructures; lock-in is prevalent on the supply as well as on the demand side.
- **Uncertainty and risks:** Energy innovations are characterized by major uncertainties for investors and policy makers; risks are high as a result of uncertainty.
- **Environmental impacts:** A key driver for energy innovations are negative environmental impacts of existing technologies; energy and environmental policies are often closely intertwined.
- **Energy sector as a public service sector:** The energy sector is characterized by a high degree of regulation (due to its societal importance and because of network monopolies); public authorities as well as public service companies play a crucial role in many countries; these characteristics make the energy sector distinct from other service sectors.
- **Politics:** Strong vested interests and an active pursuit of these interests is characteristic for the domain of energy policy-making and thus a crucial component in the dynamics of new energy technologies.
- **Complexity & idiosyncrasy:** A large variety of factors play a role for emerging technologies, there is no optimal structure or recipe of how to develop a technology successfully, each technology and context has its particularities.
- **TIS structures:** For new energy technologies to develop and diffuse, supportive institutional and organizational structures including technology-specific policies are required; supportive structures partly emerge but they are also developed strategically by the actors in the field.
- **TIS performance:** TIS performance can be best assessed on the basis of key processes (functions); it is not sufficient to look at TIS structures alone to understand whether an emerging technological system is performing well or not.
- **TIS context:** Apart from the TIS itself, context developments (e.g. at the NIS or SIS level) play a crucial role for new technologies; these include the ups and downs of existing technologies and established socio-technical systems as well as of competing and complementary technological innovations. The TIS context is also the source of actors, competences (e.g. human resources), material and financial resources etc.
- **TIS life cycle:** TIS in early stages of development (e.g. fuel cell technology) may require different support than more mature systems (e.g. wind energy); in immature TIS technological expectations and legitimacy play a much more decisive role, for example.

2.4 Towards an integrated agenda on "energy innovation systems"

The above literature review has shown that energy is a prominent topic in innovation systems research. The TIS perspective has developed quite an elaborate set of empirical case studies and conceptual tools to address conditions for success of energy innovations, particularly if they imply a more radical restructuring of the prevailing energy sectors. Increasingly, we see contributions from the other innovation system schools (NIS, RIS and SIS) that aim at tackling problems of energy innovation processes. As mentioned earlier, these different approaches rather complement each other, which is why it might be a worthwhile endeavor to explicitly compare the contributions of the different perspectives to the explanation of emerging (energy) technologies.

The conceptual complementarities can be explored along different lines. Among these are comparative designs of different TIS-structures and processes that are located in different national contexts. Another promising inroad could be the connection between NIS approaches and management studies research on emerging business models and value chain creation (such as in Provance et al. 2011). Also, the NIS perspective certainly emphasizes the role of macro-institutional conditions such as the prevailing science system, regulations on property rights, synergies among different aspects of industrial policy, national cultural preferences, etc., which might be overlooked in studies that are narrowly focusing on single technologies. In a similar vein, the RIS perspective focuses even more explicitly on existing industry networks and their embedding in local and regional cultures, the importance of regional labor markets, university systems, etc. Strong institutional embedding was shown to be decisive for overcoming the high levels of uncertainty typical for early energy innovations (Dewald and Truffer, 2012). Finally, a SIS perspective is very attentive to the role of incumbent actors in the energy system, their likely support or opposition to developments in certain technological fields (Erlinghagen and Markard, 2012). Furthermore, the impact of large scale institutional reforms (such as privatization, deregulation or liberalization) on the innovation management in a whole sector might be more consistently analyzed when a sectoral focus prevails.

Therefore, we see a high added value in striving for a more integrated view on "energy innovation systems". As this potential has not yet been widely identified and no overarching "energy innovation system community" exists yet, we propose to discuss potential inroads to a broader agenda starting from current research needs that have been identified within the TIS community.

3 Major challenges in developing the TIS research agenda[3]

Despite the recent progress in TIS studies, there are several conceptual and methodological challenges still pending. In the following we list some key topics where future research seems to be particularly beneficial.

3.1 Core concepts

a) General

It is widely acknowledged that actors and institutional structures are the key elements (or components) of technological innovation systems. Actors and institutions are interrelated through different kinds of networks and commonly contribute to the development of diffusion of a novel technology. However, recent contributions have also suggested differentiating further TIS elements, including technology, knowledge, or system resources (e.g. Bergek et al. 2008a; Sandén and Hillman, 2011; Musiolik and Markard, 2011). System resources, for example, can be a useful concept to explain the system-building strategies of TIS actors and the resulting positive externalities.

b) Functions concept revisited

The system functions are one of the major innovations of the TIS concept in recent years. They have triggered a whole wave of empirical studies and many new insights. At the same time, the concept has also created some confusion as different scholars have a different understanding of what functions actually are and whether the term as such is misleading or not (Bergek, 2012). Moreover, it is still unclear whether we have already come up with a sufficient set of (seven) functions or whether there are any functions missing (e.g. value chain creation or system building, cf. Musiolik and Markard, 2011 and Musiolik et al, 2012). Another topic that requires further attention and conceptual reflection is the relation between TIS structures and functions.

c) Actors, networks and intermediaries

The predominant view on TIS actors is that they are working together (mostly implicitly through the guidance of institutional structures) towards the overall system goal, which is the development and diffusion of the focal technology. However in empirical analyses, we see that firms often pursue specific strategic interests, e.g. as they positively communicate and inflate the prospects of 'their' technology (Konrad et al., 2012) or support specific standards that match their already existing competences (Musiolik and Markard, 2011). Firms and other actors also contribute to system building in a strategic way (Musiolik et al, 2012). Against this background is it essential to further our analysis of actor roles and strategies in TIS studies (cf. Farla et al., 2012).

So far, the TIS concept distinguishes different kinds of actors in a very generic sense, i.e. firms, policy makers, research institutes, NGOs etc. At the same time, the concept of (actor) networks plays a key role for TIS scholars. While there is a common understanding that networks are important, e.g. for knowledge exchange in innovation systems, we are just at the beginning to understand alternative

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[3] The radar paper profits from synergies of a number of ongoing international initiatives in the field of energy innovation systems research. In particular, Section 3 is aligned with an ongoing initiative of an international group of scholars contributing to the TIS literature to elaborate and specify the TIS research agenda.

roles of networks. Recent research has shown that (formal) networks can play a crucial role for TIS formation and the development of supportive institutional structures in a TIS (Musiolik et al., 2012). A novel and more specific conceptualization of actors (including networks and intermediaries) could therefore address their role in system building.

d) Concept of Institutions

Regulatory, normative and cognitive institutions play a key role for the development and diffusion of innovations. In fact, it is the dynamic interplay of institutions and organizations that largely determines the course of technology development. Despite the importance ascribed to institutions and institutional change, there is little consensus on how to systematically analyze institutions and their role in innovation processes in general and technological innovation systems in particular. This is all the more striking in fields such as 'sustainable innovations', where environmental regulations, public support programs and normative views can be strong institutional drivers, while at the same time the technology is opposed by established institutional structures that support less sustainable technology alternatives.

What will be needed is a more elaborated conceptual understanding of institutions and the interplay of institutional structures for the development of new technologies. In addition, we will have to address the question of how actors strategically change and create institutional structures (cf. sub-section 3.1.c).

e) TIS life-cycle and transitions

Scholars working with the TIS approach have not yet developed a conceptual framework that explicitly elaborates on the evolution of innovation systems over time or explains socio-technical transitions, i.e. fundamental, multi-dimensional changes of established socio-technical systems through innovation system dynamics. Such a "TIS based" transition framework could deliver insights that are complementary to the already established multi-level perspective (e.g. Rip and Kemp, 1998; Geels, 2002). In parallel, conceptual development will have to concentrate on the life-cycle of technological innovation systems, i.e. the particularities and dynamics that occur when a TIS develops from a very early, embryonic stage into more mature structures with different system properties (e.g. dominant design, path-dependencies).

3.2 Methodological issues

a) Measurement of functions:

A central task in a TIS analysis is to assess the strength of the functions. This can be done in a number of ways which include conventional indicators such as patents, but also less conventional ones such as measures of the supply of specialized human capital and of the legitimacy of a new technology. Interview based assessments are common (e.g. Hellsmark, 2010). Negro et al. (2007) and Suurs et al. (2009) combine these with quantitative analyses of events. Van Alphen (2011) uses expert assessment to quantify the strength of the functions in five countries. A number of tools have, thus, been tried but as yet, no standard combination of indicators for measuring the strength of the functions has been developed. A research task would be to review and empirically test possible indicators for each function, the aim of which is to recommend a standard set of indicators that allows for comparisons across technologies, time and space in the field of environmental innovations (Jacobsson and Bergek, 2011).

b) System boundary setting

In many TIS studies, system boundaries are defined ad hoc and without much consideration of the implications this has for the findings. Applying national boundaries, for example, becomes increasingly problematic as TIS in the energy sector typically span many countries and even develop into global industries (as in the case of PV or wind energy). Future research has to engage more explicitly with the question of how to conceptualize and identify system boundaries. We might also want to compare the suitability of boundaries that are defined from the beginning of a study with an emerging boundary setting in the course of the analysis (e.g. Bergek et al., 2008a, Carlsson et al., 2002).

c) Extending the methodological tool-box

As network formation is arguably of key importance for TIS emergence and performance, social network analysis promises a new and more formalized methodological inroad for analyzing how actors get connected to each other and how they jointly develop a conducive environment for innovation. Promising fields of application comprise the identification of spatial and technological boundaries of TIS (Binz et al. in preparation, Sanden and Hillmann, 2011), in-depth analysis of actor networks underlying specific TIS functions or explanations on the determinants of successful or failing cooperation among complementary actor groups. So far, TIS studies have not made much use of recent advances in the modeling of socio-technical transitions (cf. Safarczynska et al. 2012). From these and other new methods we expect interesting, complementary insights to the more 'traditional' TIS analyses prevailing up to now.

d) Predictive models and strategic planning

Recent work in TIS has ventured into developing the concepts further for forward looking contexts. Markard et al. (2009) for instance presented a method for "innovation system analysis" that identifies alternative coherent techno-organizational variants that could represent potential but not yet realized development trajectories for a specific TIS. In that context, scenario methods gained increasing attention as a means to identify future context conditions, which would support or hinder the further development of TIS (see e.g. Truffer et al. 2008). Along these lines, other research has ventured into identifying specific capability constellations represented by alternative value chain configurations. These enable the identification of future development prospects TIS (e.g. for the urban water management sector see Gebauer et al. 2012). These methods are likely to have an important role to play in future attempts to connect TIS analysis with the management literature (see 3.1.c) and probably also in the context of technology policy (see 3.4).

3.3 Considering contexts more explicitly

If we think of technological innovation systems as socio-technical systems that do not just exhibit specific 'internal' dynamics but are also affected by developments in a broader context (e.g. new technologies that emerge in adjacent sectors), then we will need a more elaborated understanding of context structures and context dynamics.

a) Spatial contexts: National, regional, global, multi-scale

Space has been absent from much of the actual TIS research (Carlsson, 2006; Coenen et al., 2012; Truffer and Coenen, 2012; Coenen and Truffer, 2012). Only very recently, TIS studies have started to address the implications of regional embedding (Dewald and Truffer, 2012) and the international and global dimensions of technological innovation systems (e.g. how global developments in a specific technological field affect the TIS in a selected country (cf. Binz et al., submitted). Therefore, we expect TIS research to greatly benefit from addressing issues such as how technological innovation systems connect on a regional, national and global scale or how to analyze the geographical reach of TIS (cf. 3.2b).

b) Sectoral contexts/regimes

The review of different innovation system perspectives above has highlighted the potential that rests in a more systematic exploration of the overlap and intersection of emerging and established systems of innovation. Future research should address questions such as the following: How do TIS interact with established socio-technical regimes? How do TIS link up with established institutional fields (cf. section 3.1d)? It would be desirable to introduce a more elaborate analysis of established sectoral systems (or socio-technical regimes) as specific context elements and analyze more comprehensively how they affect the TIS under study (cf. Markard and Truffer, 2008b; Wirth and Markard, 2011). This then facilitates the analysis of the interplay of incumbent and emerging technologies (e.g. nuclear and renewable energies) in a similar way as scholars who use the multi-level perspective (Geels, 2002) do.

c) TIS context and TIS – TIS interaction

Another way to structure the context is to include other technological innovation systems that affect the focal TIS either in a complementary or in a competitive way (or both) (Jacobsson, 2008; Sanden and Hillmann, 2011). For the case of biogas, Wirth and Markard (2011) have shown how the emerging TIS for Bio-SNG in Switzerland was hampered by the developments in various technological fields that compete for the same biomass resources (here: wood).

3.4 Policy implications

As mentioned above, the TIS framework was developed as a policy tool to guide policy makers in designing interventions which were specific to a particular system. Implementing such policies raises the question of how policy makers can identify the processes that are of critical importance to the dynamics of specific technologies and to which policy intervention should be addressed. The prime contribution of TIS-related analyses, so far, has been to use the functions of innovation systems as a tool for pinpointing system weaknesses which then act as a guide for policy makers (Jacobsson and Bergek, 2011). Of course, other actors interested in influencing system dynamics (individual firms, networks of firms, academics, interest organizations) may also use system weaknesses as a guide for their actions (investment, lobbying etc).

More work is required along at least two lines. A first is the competence, organisation and integrity of public policy bodies. Identifying relevant system weaknesses necessitate that policy makers have a high analytical and deep domain-specific competence. Moreover, using system thinking implies that a range of government bodies needs to be involved in the analysis and implementation of policy.

Competence to coordinate policy intervention must, therefore, exist. Analysing the competences and organisational set-up required to implement TIS in policy making is, therefore, a worthwhile field for research. Second, a system approach implies that we should think of policy instruments as "systemic instruments" that are applied to deal with system weaknesses. These instruments go much beyond the neoclassical focus on relative prices etc. and include e.g. instruments to strengthen the legitimacy of new technologies. More work is required to specify the range of "systemic instruments" and assess their usefulness in various contexts (Weber and Rohracher 2012, Wieczorek and Hekkert, 2012).

4 Development trends in the most recent energy EIS literature (2010-2011)

We will now turn to a quantitative and qualitative overview of the recent energy TIS literature. This section will reflect the thematic foci of the research agenda sketched in section 3 with recent publications and aims at triangulating these agenda dimensions with recent work in the field. A comprehensive literature research in the Scopus database was conducted, covering publications from 2010 and 2011. The search was structured in three consecutive steps (see figure 2): First, papers that contribute to the conceptual core of technological innovation systems were identified and categorized into thematic clusters. Then, these results were complemented with a very broad search string (looking for 'innovation', 'energy' and 'system') resulting in a large but mainly unfocussed set of publications that provide a feeling for the larger scholarly context of energy TIS research. Finally, publications that combine an innovation system focus with the most popular empirical fields in the wider context were categorized according to the thematic clusters developed in step 1.

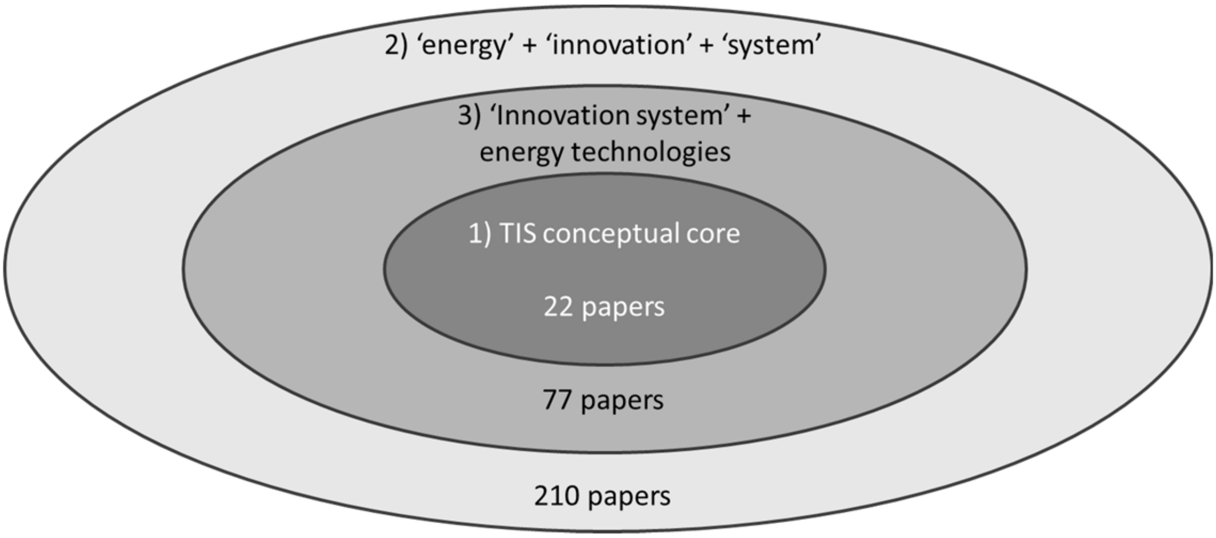

Figure 2: Scheme of analysis and number of identified papers

4.1 Publications in the conceptual core of TIS research[4]

21 papers in the Scopus database between 2010 and 2011 contained "technological innovation system" in the title, keywords or abstract. 18 of them contribute directly to the TIS concept. Except for four papers (Binz et al., 2011), Jacobsson and Perez-Vico (2010), Pellegrin et al. (2010) and Leydesdorff and Zawide (2010)) all authors strongly base their contribution on energy related case studies. 4 papers by Chinese authors were excluded from the analysis as they use the term "technological innovation system" as a buzzword in an unrelated context (e.g. patent network analysis, systems theory, empirical cases in the Chinese defense sector), without or only with 'pro forma' reference to TIS literature.

[4] Search string: TITLE-ABS-KEY("technological innovation system") AND (PUBYEAR = 2010 OR PUBYEAR = 2011) AND SRCTYPE(j)

Five papers had to be added to this list as they contribute to TIS research, but do not name the concept in the title, abstract or keywords (Jacobsson and Bergek 2011, Meijer et al. 2010, Jacobsson and Vico 2010, Smith and Grin 2010 and van den Bergh et al. 2011). 22 core conceptual papers thus remained for a detailed analysis.

Five thematic clusters emerged inductively out of this literature review: i) Policy / governance of TIS, ii) conceptual clarifications, iii) actor strategies, iv) functional approach to TIS and v) extending insights from TIS studies to other literatures. The core papers can be allocated to these thematic clusters as follows:

a) Policy implications / Governance of TIS

Authors	Topic	Case study	Country	Concepts	Approach
Jacobsson and Bergek (2011)	TIS policies, system weaknesses	several	diverse	TIS, MLP	Review
Vasseur and Kemp (2011)	Effect of policy on TIS evolution	PV	Germany, Netherlands	TIS	Case study
Hillman et al. (2011)	Framework for analyzing IS governance	none	diverse	TIS, MLP, governance	Review

Policy and the governance of TIS are key topics in three contributions. Two strands of argumentation can be identified in the literature: In the first paper by Jacobsson and Bergek (2011), TIS is used as an approach to formulate policies that sustain diffusion of renewable energy technologies. It is argued that technology specific policies could be derived from a system weakness – based TIS approach and that such an approach could enhance policy advice in a sustainability transitions framework. The other two papers discuss how specific policies and governance modes influence the evolution of innovation systems by applying a political science and governance approach.

b) Considering contexts more explicitly

Authors	Topic	Case study	Country	Concepts	Approach
Sanden and Hillman (2011)	Interaction among technologies in IS	biofuels	Sweden	STS, TIS	Review, case study
Wirth and Markard (2011)	Influence of context factors on TIS evolution	synthetic natural gas	Switzerland	TIS	Case study
Leydesdorff and Zawdie (2010)	Triple helix perspective on innovation systems	several	diverse	Triple helix, IS	Review
Coenen and Diaz Lopez (2010)	Comparison of system approaches to innovation	several	diverse	SIS, TIS, ST-systems	Review
Pellegrin et al. (2010)	Role of innovation networks in IS	oil industry	Brazil	NIS, RIS, SIS, TIS, IN	Review, case study

The thematic cluster focusing on conceptual clarifications and the context of TIS can be divided in to two main streams: The first two papers address basic conceptual elements of TIS and how they relate to the context of a focal TIS. Sanden and Hillman focus on the conceptualization of technology and on how different technologies interact. They argue that technologies have to be conceptualized as socio-technical systems and that beyond competition, other interaction modes like symbiosis, neutralism, parasitism, commensalism and amensalism are possible. Wirth and Markard try to understand how dynamics in the context influences developments inside a focal TIS. They argue that developments in related sectors can be of crucial importance for TIS evolution.

The remaining three papers also discuss how context influences a focal technological innovation, but do so by focusing strongly on related innovation system concepts. They all discuss how (interacting) innovation systems at other levels like NIS, RIS, SIS or a triple helix perspective on IS define the context for a focal TIS.

c) Actor strategies

Authors	Topic	Case study	Country	Concepts	Approach
Musiolik and Markard (2011)	Actors forming strategic networks for TIS buildup	Fuel cells	Germany	TIS, management	Case study
Meijer et al. (2010)	The role of entrepreneurs in innovation systems	Biomass combustion	Netherlands	Entrepreneurship	Case study

This small thematic cluster revolves around the question how strategic behavior of TIS actors can be conceptualized and analyzed. Musiolik and Markard argue that TIS actors proactively build up strategic networks to sustain specific technologies which in turn provide critical resources to system build up. Meijer et al. take an entrepreneurship perspective and analyze how perceived uncertainty influences the strategic behavior of entrepreneurs in innovation systems.

d) Functional approach to TIS

Authors	Topic	Case study	Country	Concepts	Approach
Dewald and Truffer (2011)	Market formation in TIS	PV	Germany	TIS, management	Case study
Dantas (2011)	Knowledge accumulation in TIS	Biofuels	Brazil	TIS	Case study
Jacobsson and Vico (2010)	Effects of academic R&D on TIS functionality	Diverse	Diverse	TIS	Review
Suurs et al. (2010)	Cumulative causation in emerging TIS	natural gas in transport	Netherlands	TIS	Case study
Praetorius et al. (2010)	Functional TIS analysis	micro-generation	UK, Germany	TIS	Case study
Hudson et al. (2011)	Functional TIS analysis	micro-CHP	UK, Netherlands	TIS	Case study
Van Alphen et al. (2011)	Functional TIS analysis	CCS	US, CA, NO, NL, AU	TIS	Case study

The functional approach to TIS is still the most popular field of activity in energy TIS studies. Papers in this cluster follow two routes of argumentation: The first three papers strive at a more precise conceptualization of processes that work in specific functions or the overall functional pattern of a TIS. So far contributions only focus on the 'market formation' and 'knowledge creation and diffusion' functions.

The second stream of four publications applies a functional approach to TIS empirically in order to derive implications on cumulative causation processes in early development stages of a TIS or to formulate technology specific policy advice.

e) Extending insights from TIS studies to other literatures

Authors	Topic	Case study	Country	Concepts	Approach
Smith et al. 2010	Potential contributions of TIS to the MLP framework	None	none		Review
Van den Bergh et al. (2011)	Potential contributions of TIS to the MLP framework	None	none		Review
Foxon et al. (2010)	TIS and MLP based transition pathways	Electricity system	UK	MLP, TIS	Review, case study
Binz et al. (2011)	Applying TIS to leapfrogging literature	water recycling	China, global	TIS, leapfrogging	Case study
Huertas et al. (2010)	Using TIS for evaluating stakeholder acceptance	Bioethanol	Brazil	TIS	Case study

Papers from this thematic cluster address the potential fruitful overlaps between TIS and other strands of literature. Most publications define points of mutual interest with sustainability transitions concepts and especially the multi-level perspective on technological transitions (MLP). The first two papers are extended reviews, whereas the third paper tries to develop an analytical framework for analyzing transition pathways based on a combination of TIS and MLP concepts. The last two papers apply the TIS approach as an analytical framework for other related literatures, namely to the literature on technological leapfrogging in newly industrializing countries and as an analytical tool to assess stakeholder acceptance of new technologies.

The above list of thematic clusters was developed inductively and is to be taken as a first indicative overview. Some papers would be attributable to different clusters and others might be categorized differently. As an example the paper by Jacobsson and Bergek (2011) also discusses how TIS and MLP relate to each other, so it could also be attributed to the last cluster. The papers of Binz et al. (2011), Dewald and Truffer (2010) or Dantas (2011) as other examples, all apply a geographic perspective to TIS, so they could also be categorized as a 'geography of TIS' cluster.

Half of the publications in this core group is authored by the largest research groups contributing to the field, e.g. at Chalmers University, Utrecht University as well as at Eawag. Interestingly, three papers cover the biofuel case in Brazil, two of which are authored mainly by Brazilian authors. Contributions to the conceptual core, thus, seem to expand geographically and qualitatively to newly industrializing countries and especially to Brazil.

4.2 The wider scholarly context of energy innovation systems research

In order to complement the above overview of the core conceptual contributions in energy TIS research, another search string containing energy, innovation and system as keywords was used in

Scopus.[5] This broad search string generated 210 results, which however contained many unrelated articles from distant academic fields. 54 engineering based papers were consequently removed from the dataset and the remaining 156 papers were categorized according to their abstracts.

Insights from this extended database:

- Extending the focus reveals about 60 additional papers in the energy field which are more or less closely related to TIS. Overall, about 80 papers (including the ones already discussed in the section above) are interesting in the wider sense for TIS research, though already quite distant from the conceptual core of innovation system studies.
- Most plentiful and fruitful insight might be derived from contributions from political sciences, urban studies, geography, economics and management.
- Empirical fields are very broad: From PV to wind, hydrogen, bio-ethanol, CCS, solar water heater to palm oil and smart grids. Also more aggregated perspectives (renewable energy, low-carbon economy, etc.) are referred to in literature relatively often (see table 2). Renewable energy, biofuels, energy infrastructure, hydrogen/fuel cells, wind and photovoltaics are the core empirical fields (see table 2).
- Interestingly, a few of the listed engineering papers take the socio-economic context of renewable energy technologies into account and apply a socio-technical perspective, by discussing how (especially the economic and in some cases institutional) context of “clean” technologies matters for their success.

5 TITLE-ABS-KEY("energy" AND "innovation" AND "system") AND (SUBJAREA(soci) OR SUBJAREA(busi) OR SUBJAREA(econ) OR SUBJAREA(busi) OR SUBJAREA(ener)) AND (PUBYEAR = 2010 OR PUBYEAR = 2011) AND SRCTYPE(j)

Table 2: Empirical field of application

Empirical case	Number of papers
none	9
Renewable energy	9
biofuels	7
energy infrastructure	5
hydrogen, fuel cells	5
photovoltaics	5
wind	5
climate change mitigation	4
energy policy	3
Environmental governance	3
low carbon society	3
Carbon capture and storage	3
eco-buildings	2
micro-generation	2
coal power	1
factory automation	1
global energy modeling	1
green regions	1
micro-CHP	1
natural gas	1
water	1
palm oil	1
energy input prices	1
Renewable energy policy	1
smart grid	1
solar water heater	1
advanced geothermal systems	1
Total	78

- Bioethanol and biofuels are a surprisingly popular empirical field which appears to be booming especially in case studies in Brazil
- A majority of contributions is focusing on renewable energy technologies, only very limited number of papers refers to conventional power generation technologies like natural gas or coal power
- Modeling and especially economic models in the renewable energy field are relatively popular and applied in many studies with an economics background
- Policy analysis, especially of interventions for sustainable energy (and assessment of policy intervention) is booming recently.

4.3 Triangulating the conceptual core and empirical context of energy TIS research

In a last step, a search string containing "innovation system" or "system of innovation" was combined with the technological fields that were named most in the literature search in section 4.2[6]. Table 3 summarizes the use of these keywords in paper abstracts.

Table 3: Appearance of keywords in energy TIS publications

Technology	Keywords	Papers
Photovoltaics	PV, photovoltaic*	15
Wind power	wind, wind power	32
Biofuel	biofuel*, bioethanol	22
Biogas	Biogas	8
Hydrogen, fuel cells	fuel cell, hydrogen	17
CCS	CCS, carbon capture and storage	9
Combined heat and power	micro-CHP, CHP, combined heat and power	7
Electricity system, smart grid	smart grid, electricity system, energy system	25
Renewable energy, sustainable energy	sustainable energy, renewable energy, bioenergy, low carbon	46
Hydropower	hydro, hydro power	3
Nuclear power	Nuclear	8
Coal power	coal, coal power	10
Gas power	Natural gas, gas power	7
Total, duplicates removed		77

The results for each of these empirical fields were captured in a separate database and then combined to one single list, deleting all duplicates. With this approach, the retrieved database now contains 18 of the 22 key conceptual papers as well as a comprehensive set of closely related papers from other research communities.

The list of thematic clusters from the preceding section was accordingly used for categorizing the papers in this extended database. 62 of the total 77 publications could be allocated to one of these clusters (see table 4)

[6] (TITLE-ABS-KEY("innovation system" OR "system of innovation") AND ("keyword X" OR "keyword Y" OR "keyword Z") AND (PUBYEAR = 2010 OR PUBYEAR = 2011) AND SRCTYPE(j)); Keywords summarized in Table X.

Table 4: Thematic clusters in recent energy TIS research

Thematic cluster	Number of publications
unclear	15
Functional approach to TIS	14
Considering contexts more explicitly	12
Policy implications / TIS governance	11
Application to other literatures	8
Geography of TIS	7
Actor strategies	6
Methodological issues	4
Total	77

The list of thematic clusters in this triangulated database had to be extended by two categories: Geography of TIS and methodological contributions. 7 papers take an explicit geographic perspective on innovation systems, mainly focusing on regional innovation systems and their connection to higher level system structures. As stated before, this list could additionally be extended by 3 papers from the conceptual core of TIS research. In addition, 4 papers exclusively discuss methodological approaches for innovation system analysis, namely foresight, modeling, system analysis and technology assessment.

A more detailed overview of each of the thematic clusters can now be provided:

- Policy / governance of TIS: Publications that use an innovation system approach to formulate or evaluate technology specific policies are most plentiful in the literature. There are only few additional contributions which discuss governance of TIS in the extended database.
- Considering contexts more explicitly: Here, Mostafavi et al. (2011) add an interesting general conceptual idea by arguing that innovation systems should be understood in a "system of systems" perspective. Three additional studies further concern the influence of context factors on TIS. They try to discuss TIS context either from a NIS or innovation network perspective, but do so in ways which are quite remote from TIS research. Finally, 6 additional papers discuss the relations between different IS concepts, relying on either SIS, RIS or NIS approaches. However, except for Coenen and Lopez (2010), none of them make explicit reference to TIS.
- Actor strategies: This thematic cluster is not covered by a lot of literature in the wider context of energy TIS studies. 3 of the 6 additional papers in this field are based on the management literature, the rest applies a transition, economics or NIS perspective.
- Application of the functional approach: In total, 7 studies discuss processes in specific TIS functions in more detail. 3 additional papers focus on knowledge creation and diffusion, whereas one paper by De Souza and Hasenclever (2011) looks at the standardization process which is related to the "guidance of the search" function. Application of the functional approach to specific fields of technology appears to be the dominant focus in the 7 papers in this thematic cluster.
- Application of TIS to other literature: Two papers use innovation system approaches to improve conceptualizations in other strands of literature. In addition to Binz et al. (2011), also Fu and Zhang (2011) apply an IS perspective to assess leapfrogging potentials in Indian and Chinese PV

industries. Finally, 6 papers combine a TIS perspective with transition theories. Three papers use TIS as a tool to assess niche processes in an MLP perspective, whereas the other 3 papers contain general reviews on how to fruitfully combine these two perspectives.

Apart from thematic clusters, the retrieved literature database revealed the following general features of energy TIS literature:

- About 70% of the empirical studies are based on single case studies. 20% compare different cases and about 10% are conceptual discussions based on literature reviews.
- An interesting and growing stream of literature focuses on the way policy influences TIS evolution by taking up political science or governance perspectives. Featured topics cover public-private partnerships, triple helix interaction, as well as planning processes, especially in urban contexts.
- Application of the context is expanding geographically: There is a growing stream of articles that applies TIS to developing and newly industrializing countries to assess their catching-up strategies or to discuss development issues. Besides the usual European countries, especially Brazil, China (also Taiwan) and increasingly the US are increasingly used for empirical studies (see table 5). Brazilian authors deserve special mention here for making conceptual contributions to the energy TIS's core agenda (e.g. Dantas, 2011; Pellegrin, et al. 2010; Huertas et al. 2010)

Table 5: Geographic focus of energy TIS studies

Country focus in case studies	Number of papers
Diverse	14
None	12
China	7
Brazil	7
UK	6
Unclear	5
Taiwan	3
Germany	3
USA	3
Netherlands	3
Western Europe	4
Eastern Europe	3
Asia	3
Others (Morocco, Argentina, Tanzania, Canada)	4
Total	77

- Finally, 5 journals stand out as the most popular outlets for energy TIS research: Energy Policy, Research Policy, Technology Analysis and Management, Technological Forecasting and Social Change and the International Journal of Technology and Globalisation (see Table 6)

Table 6: Outlets of energy TIS research

Journal	Number of papers
Energy Policy	8
Research Policy	5
Technology Analysis and Strategic Management	5
Technological Forecasting and Social Change	4
International Journal of Technology and Globalisation	4
Industry and Innovation	2
Renewable Energy	2
Journal of Technology Management and Innovation	2
Industrial and Corporate Change	2
Environmental Innovation and Societal Transitions	2
Agricultural Systems	2
Others	39
Total	77

4.4 Discussion of most recent trends in energy TIS research

Energy innovation systems research evolves around a relatively small core of conceptual contributions, which are provided mainly by research groups in Sweden (Chalmers University), the Netherlands (Utrecht University), Switzerland (Eawag) and the UK (e.g. SPRU, University of Leeds). Publications in the wider context are relatively plentiful and even though most of them are not directly related to TIS there appears to by a considerable potential of cross-fertilization from political sciences, management studies, economic geography and especially from plentiful publications on related innovation system concepts. Referring back to the research agenda sketched in section 3, the thematic clusters revealed in the review of recent literature show that the agenda dimensions can be extended mainly in 3 dimensions: 1) A growing body of literature tries to further conceptualize the processes that work inside specific functions. This approach arguably holds a high potential for future conceptual clarifications that go beyond the general open questions with the functional approach as discussed in section 3. So far, only knowledge creation and market formation are covered by this new line of research, extending this approach to the other TIS functions is thus encouraged. 2) Another emerging stream of literature which was not referred to in section 3 is the governance of TIS, which also holds promising potential for conceptual clarifications. 3) Increasing activity appeared in studies on geographic dimensions of TIS (mainly at a regional or urban scale) and application of the concept is diffusing strongly to newly industrializing countries. Finally, institutional analysis of TIS was mentioned in section 3 as an important agenda topic in TIS research. The literature analysis did however not identify a lot (if any) attention to this topic. Given the interesting conceptual input that institutional perspective could provide, future research in this field should be encouraged.

5 Conclusions and outlook

The aim of this literature review was to provide an overview of current trends and challenges in energy related innovation systems research by elaborating on major conceptual, methodological and empirical developments in the field in order to identifying promising future research lines. We have seen that energy innovation is a vibrant field of application for innovation system concepts. So far, the field seems to be much more strongly developed in the TIS tradition than in the others. However, NIS, RIS and SIS scholars are increasingly discovering the energy sectors as legitimate and productive application fields.

As the different innovation system concepts share a number of similarities and can be traced back to the same foundational concepts, it seems worthwhile to analyze in how far an integrated "energy innovation systems" approach could be formulated (Coenen and Diaz-Lopez, 2010; Weber and Rohracher 2012). We see a high added value in such an endeavor defining a potentially productive research field to which all sorts of innovation system scholars could contribute. Given the very unbalanced development stage of the different approaches, we proposed to elaborate an inroad into this upcoming field from the point of view of the TIS research community. The research lines that were identified in section 3 delimit a broad field for future research activities that would encompass and invite also scholars rooted in different traditions.

For instance there is an increasing interest in conducting comparative analyses of innovation system development in different national contexts (see van Alphen et al. 2010; Marinova and Balaguer 2009). TIS scholars are likely to gain substantially by considering approaches rooted in the NIS or RIS traditions. The latter approaches are likely to emphasize technology and sector spanning interdependencies in specific spaces (countries, regions) that a single-technology approach is likely to oversee (see for instance Kubeczko et al. 2006). Related to this we have to acknowledge that energy innovations increasingly take place in different countries across the globe. For instance emerging economies like, China, Brazil or India have become very important players in the field of energy innovation and cleantech industry formation. This trend is likely to continue and expand to other countries. Concepts have therefore to identify the emerging (multi-scalar) global structure of innovation systems which is influenced by several national technology policy strategies concurrently (Binz et al. 2012).

Regarding the transition problem, i.e. the longer term prospects of whole energy sectors in which emerging renewable technologies gain more and more prominence, energy innovation systems research should more explicitly focus on incumbent sector players and how they interact and interfere with emerging technologies (e.g. Erlinghagen and Markard, 2012). This requires more attention to regulatory incentive schemes and their influence on the prevailing innovation management cultures in the energy sectors (as described by Rogge and Hoffman 2010; Markard and Truffer 2006; or Cheon and Urpelainen 2012). Ultimately, what is at stake is an explicit model of sector transformation (similar to the transitions concept in the MLP tradition) that goes beyond a simple substitution of old technologies by new ones (cf. section 3 and Weber and Rohracher, 2012).

A third major line of future research relates to the interconnection of energy innovation systems research with management studies in order to better understand the role of (public and private) firms in the dynamics of emerging technological fields. We expect that the strategies and resources of organizational actors have a significant influence on how innovation systems develop and perform (Markard and Truffer 2008a; Provance et al. 2011). Recent contributions have also shown that firms and inter-firm networks can play an important role in creating collective resources at the innovation system level, thus contributing to innovation system building (Musiolik and Markard, 2011; Musiolik et al. 2012). This will open up new avenues to bring lessons from energy innovation research also to the attention of decision makers in industry and government (Farla et al., 2012).

Finally, we see a definite need to further work on improving policy advice from energy innovation system research. This relates to all aspects of innovation systems development: Measuring performance, assessing the functions, identifying blocking mechanisms, positioning specific TIS within an industry life cycle, etc. Policy makers may be at the regional, national or international level (like the EU or the OECD) (Weber ad Rohracher 2012). In particular, these policies have to be positioned in an increasingly global context and therefore also considerations of international interdependencies have to be taken into account (Truffer, 2012).

Summarizing the evidence collected in this Radar paper, we may conclude on a very positive note: Energy innovation system research is an emerging field with high promises. There is an extensive literature on which research can build but also a large room for further development and application of the core concepts. We consider that this field is vibrant and evolving and therefore an updated assessment of the identified trends in this literature review promises to add considerable insight into this highly important field of research.

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7 Appendices

7.1 Appendix A: Publications in the conceptual core of TIS studies

Binz C., Truffer B., Li L., Shi Y., Lu Y. 2011. Conceptualizing leapfrogging with spatially coupled innovation systems: The case of onsite wastewater treatment in China. Technological Forecasting and Social Change.

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7.2 Appendix B: Literature list from triangulating empirical core and empirical context of TIS

Adzic S., Birovljev J.; 2011; The strategic framework for sustainable development of agro-food industry the case study of Vojvodina; Technics Technologies Education Management; 6; 4; 916; 929

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Carr K.; 2010; Minister releases strategy report at symposium; Appita Journal; 63; 3; 173; 174

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Coenen L., Diaz Lopez F.J.; 2010; Comparing systems approaches to innovation and technological change for sustainable and competitive economies: An explorative study into conceptual commonalities, differences and complementarities; Journal of Cleaner Production; 18; 12; 1149; 1160

Cook P.; 2010; Regional innovation systems: Development opportunities from the 'green turn'; Technology Analysis and Strategic Management; 22; 7; 831; 844

Cooke P., Porter J.; 2011; Media convergence and co-evolution at multiple levels; City, Culture and Society; 2; 2; 101; 119

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