Technical University of Denmark

Differences and similarities of energy innovation systems – comparison of five technology areas in Denmark

Borup, Mads

Published in:
Proceedings of International Sustainability Transitions Conference (IST 2016)

Publication date:
2016

Document Version
Peer reviewed version

Link back to DTU Orbit

Citation (APA):
Borup, M. (2016). Differences and similarities of energy innovation systems – comparison of five technology areas in Denmark. In Proceedings of International Sustainability Transitions Conference (IST 2016) Wuppertal Institute for Climate, Environment and Energy.

Differences and similarities of energy innovation systems – comparison of five technology areas in Denmark

Mads Borup, Technology and Innovation Management division, DTU Management Engineering, Technical University of Denmark, mabo@dtu.dk.

Abstract

This paper presents a study of the energy innovation systems concerning five technology areas in Denmark: biomass energy, wind power, solar cells, fuel cells & hydrogen and energy efficiency technology. The study shows that the characteristics of the innovation systems differ significantly between the areas amongst other things concerning actor landscapes, market formations, and patterns of learning and interaction. This is despite the common context of Danish society and Danish energy systems, policy and institutions. An increase in maturity has appeared in some of the areas over the latest decades. Along with the increase in maturity, a number of new challenges have appeared. Despite internationalization and open economies, the national, domestic level is of significant importance. The paper contributes to current research discussions on the context relations of technological innovation systems, including the significance of the international dimension and the relationships to the established energy sector and incumbents.

Introduction

The characteristics and dynamics of innovation systems with respect to sustainable energy technologies constitute a topic of important relevance for transition processes and change towards sustainable energy systems. The studies of innovation systems with respect to energy technologies have shown that energy innovation systems differ considerably between technology areas and from one country to another. Current research discussions in the field amongst other things concern the context relations of technological innovation systems, the significance of the international dimension, and the relationships to the established energy sector and incumbents (Bergek et al. 2015).

This paper contributes further insight in these issues by reporting on an analysis of the innovation systems with respect to five areas of energy technology in Denmark that are all considered to play a role for the transition towards sustainability: biomass energy, wind power, solar cells, fuel cells & hydrogen, and energy efficiency technology. The analysis identifies characteristics with respect to actor landscapes, learning patterns, market formations, and integrations with the existing energy sector and other industries. The technology areas are selected among those that in the latest decades have appeared centrally in the public support for research and development and in the general policy agenda for making a change to more sustainable energy systems in Denmark. The three first mentioned areas are renewable energy production technologies while fuel cells and hydrogen are about energy conversion technology and energy carriers. The last area, energy efficiency technology is a broad area that covers many different efficiency technologies, but obtains a degree of inner cohesion through being a strategic effort area on political and societal level.

The study is carried out employing the technology innovation system theory perspective with its emphasis on actors, networks, and institutions and on seven key functions for the performance of the innovation systems: entrepreneurial activities, knowledge development, knowledge diffusion, guidance of search, market formation, resource mobilization and legitimacy creation (Hekkert et al. 2007, Bergek et al. 2008). In combination with this, conceptualization of types of knowledge and learning from general innovation and innovation system literature is employed. Here, the importance of not only formalized scientific knowledge development but also entrepreneurial and industrial learning-by-doing, learning-in-interaction, and learning-by-using (application based learning) has been pointed out (Jensen et al. 2007; Lundvall 1992). Of the seven functions, the three first mentioned obviously and explicitly concern knowledge and learning. The four others (market formation, legitimation, guidance of search, and resource mobilization) contain strategic elements, but however also embed aspects of learning and knowledge development. Most significantly, market formation that usually will imply industrial learning and learning from the application of the solutions. Experience gathering from developing and employing strategies, visions and policies is also an important type of learning (cf. policy learning; Gregersen & Johnson 2009). The study employs this vocabulary in order to illuminate the patterns of learning in the innovation systems of the five energy technology areas.

The study provides opportunity for comparing the technology specific innovation systems within a single country. This means that the general framework conditions, the energy sector and energy systems the technologies are intended to be implemented in, the overall policies, etc. are the same and differences identified between the innovation systems must be ascribed to other reasons than these.

Most existing studies of energy technology innovation systems are based on single case studies and focused on a single technology area in a specific country. For an overview of technologies and geographical areas addressed, see Truffer et al. (2012). Of the comparative studies there exist, the comparison most often consists in comparison of innovation systems for a specific technology area in two or three countries (e.g. Kamp 2008, Vasseur & Kemp 2011, Raven & Geels 2010, Bergek & Jacobsson 2003). The studies show that there are significant differences between the technological innovation systems in different countries and that the country-specific characteristics are of central importance for the developments. This is despite the fact that there often are international interaction and international industry and value chain networks involved in the individual technology areas and, moreover, that international communities of technology developers and scientists exist in the fields. Drawing on case studies of both wind turbines and solar technology (solar cells and solar collectors) in Germany, The Netherlands and Sweden, Jacobsson & Bergek (2004) describe the connection between industrial change and evolution of new technological systems. Moreover they show the important differences between formative phases and more mature phases of positive feedback and market diffusion of the technologies. Negro et al. (2012) identify that institutional problems in sense of lack of appropriate policy support and lack of legitimacy and actor support are the most often observed type of systemic problems and barriers for diffusion of renewable energy technologies. Secondly come problems with market structures and lock-in on existing (fossil) energy technologies. The position and power of incumbents can often play an important role in this connection.

While most studies have had focus on national level and the developments within individual countries, suggestions of analysis of energy innovation systems on global level have been made. One of the challenges of this is the availability of sufficient information and empirical material of the needed quality. In addition to international market and trade statistics, investment data and data on scientific knowledge production have been used as basis for the analysis (Gallagher et al. 2012, Binz et al. 2014). The role of international connections is also illuminated by Quitzow (2015) that describes the co-evolution of technological innovation systems for solar cells in China and Germany. Moreover, a limited number of multi-country/European studies have been carried out a.o.t. in the area of offshore wind technology. It is shown that offshore wind is not a simple development from onshore wind and that resource mobilization, legitimation, market formation and the associated structural elements and policy developments are relative weak functions at European level (Jacobsson & Kaltorp 2013). A comparative study of offshore wind innovation systems in four countries around the North Sea identified that the differences in institutional embedment in the individual countries are significant and a barrier for common developments. Moreover it is identified that the fulfillment of the different functions varies considerably between the countries. The Danish offshore wind innovation system shows to be strong concerning the functions of knowledge development, knowledge diffusion and entrepreneurial activities, while market formation is weaker than in Germany and the UK (Wieczoreka et al. 2015).

The present study contribute to the discussion of the international dimension of energy innovation systems by illuminating the connections between domestic and international relations in the Danish case. It contributes to the discussion of the understanding of openness and system boundaries in innovation system theory. Previous studies of energy innovation system dynamics in Denmark have primarily addressed wind energy and biogas (Truffer et al. 2012). Learning in interaction rather than scientific, formalized research has been identified as a characteristic of the wind power innovation system in Denmark (Kamp 2008, Garud & Karnøe 2003). A close relationship to agricultural area not only through use of agricultural waste and surplus products for energy purposes, but also through frequent use of cooperative organizational forms is shown (Raven & Gregersen 2007). The connection to the (agricultural) machine industry characterized by many small and medium sized companies is part of this. In addition to this, a recent study with comparison of the fuel cell and hydrogen innovation systems in Denmark and the United States showed that the Danish innovation system is more state centred (e.g. public R&D and cohesive public-private partnership) and characterized by SMEs than in USA where private, often larger research oriented companies are central. Moreover it is identified that there in Denmark is a degree of split between actors engaged in hydrogen technology and actors engaged in fuel cells technology despite that it is understood as one common area (Andreasen & Sovacool 2015). The above findings are on many points in accordance with characteristics of the national innovation system in Denmark in general with many small and medium sized companies and a considerable degree of cross-going interaction between organizations (Christensen et al. 2008).

Methodology and approach

The empirical study was carried out with the theory and conceptual framework described about. The study employed an overall qualitative approach supported by numerous quantitative elements. Parallel in-depth studies of each of the five areas were made. An actor-oriented methodology was employed with focus on activities by specific actors and interplay and connections between different activities on micro-level and on macro and strategic levels. Identification of actors was made by employment of roll the snowball method and use of a number of databases of actors, amongst others project databases on RD&D projects, and list of members of industry associations and interest networks. Two rounds of analysis were made, in 2011-2012 and 2015-2016.

A number of sources are employed for the empirical analysis, primarily written documents (ranging from strategy papers on sectoral, societal or network level, over accounts of micro-level activities on company, product or project level, to discussions in professional networks and media) and databases a.o.t. on projects, actors, regulatory efforts and public support programs. Preliminary analyses of the empirical material were made with use of sorting and coding of the activities related to the generalized functions in technology specific innovation systems according to the theory framework. The quantitative elements employed in the empirical analysis consist in measurements of collaboration patterns, activities and experienced driving forces through surveys (own analyses) and analysis of data from statistics on energy sector and market developments, publicly supported R&D, and business and trade of energy technology equipment. Triangulation and juxtaposition of preliminary findings was made, e.g., of accounts of technology implementation activities, governmental efforts, and market development statistics and of survey data on actor collaboration and insight from the qualitative case studies.

It can be seen as a requirement to a framework for studying sociotechnical transitions towards sustainability that it illuminates changes on regime and sector level in addition to establishment of new niches and technologies (Berkhout 2005, Kemp et al. 1998, Geels 2011). This can amongst other things be reflected in market formations and developments in legitimation. In order to emphasize this further, the present study investigated the role and degree of integration of energy sector incumbents in the technology-specific innovation systems. A typology of actors was made that distinguishes energy sector incumbents (energy companies and system operators), technology developers/suppliers, consultancies and other service suppliers in addition to traditional actor categories like public authorities, research institutions, and interest organizations. Energy consumers can also play an important role in for energy innovation and transition. Consumers were however not directly approached in the collection of data material. Similarly were retailers and distributers of energy technology products only included in cases were an explicit contribution to the innovation activities has been identified.

The function of resource mobilization was only possible to cover partly in the study. While well-covering empirical material about public R&D funding, subsidies, etc. was available, only limited material about private investments, education and workforces was accessible. With selection of the five technology areas as amongst the supported and prioritized areas in Denmark, the functions of resource mobilization, guidance of search and creation of legitimacy occur in all five technology areas and are to some degree fulfilled, at least on a basic level. All areas receives funding from national RD&D programmes in the energy area and for all areas there have been made national strategies and action plans for their development in the recent decades.

The addressing of the broad area of energy efficiency technology challenges the conceptual framework of technology-specific innovation systems, sometimes to the limit, or over the limit. The area is included for reasons of completeness. Energy efficiency and energy savings are like renewable energy supply technologies emphasized from policy side as important for transition towards sustainability. The energy efficiency area differs from the other areas, by having primarily strategies, guiding visions and legitimating discourse of energy savings as the common nominator of the area. It does not to the same degree appear as a coherent technological knowledge field or an area with a specific industrial core. It is spread over many areas. The use of the framework in this area is to some extent experimental and a test to see to what degree it can be fruitful.

Results - comparisons of five technology areas

Sizes, actor landscapes and maturity

The first observation from the set of results that shall be made is the finding that the innovation systems with respect to the five energy technology areas differ considerably in size. Biomass energy, wind energy and energy efficiency are relatively large innovation systems in Denmark, each encompassing more than 150 actors. The highest numbers of actors appear in the energy efficiency innovation system which however is also characterized by in average smaller organisations than within biomass energy and wind. Many small organisations with less than 10 employees appear. Compared to these three technology areas, the innovation systems with respect to fuel cells & hydrogen and solar cells are significantly smaller. There are less than 50 actors in the fuel cell & hydrogen area. After having been of a similar size for a number of years, the solar cell innovation system grew considerably after 2010 and now has in the order of 100 actors.

The differences in number of actors are paralleled by differences in maturity of the innovation systems in sense of the degree of market formation and application of the technologies in the Danish energy systems;

and thereby in the extensive innovative learning and experience build up that can appear in these connections. Table 1 provides an overview of the main characteristics with respect to actor landscape and maturity.

After a slow development in the application of solar cells on the Danish market in the 00s, the number of installations boomed from some hundreds to almost 90.000 installations in the period 2011-2013[1] due to establishment of a favorable policy scheme (tariff support). The boom came later than the boom in neighboring country Germany in the early 2000s. The support was changed and reduced quickly again and a starting maturing and economy of scales that had begun to appear in the industrial networks to some degree broke up again as the sales dropped to a few thousands of installations a year. The maturity in the fuel cells and hydrogen innovation system is low. Apart from a limited number of demonstration activities, there is no market application of the technologies for general, everyday energy purposes. Niche application of fuel cells for other purposes than everyday uses and general energy system purposes has appeared, e.g. in sense of auxiliary, back-up energy units. The niche applications of fuel cells have existed for a number of years, but have not led to a broader breakthrough of the technology in the energy systems and mass market in general.

Table 1: Actors and maturity in the five areas of energy technology.

	Biomass energy	**Fuel cells**	**Solar cells**	**Wind power**	**Energy efficiency**
Actors:	Many (>150)	Few (<50)	Some (order of 100), recent rise	Many (> 250)	Many (> 300)
- **Primary, leading actors**	• Energy companies (heat and power plants) • Government	• Physics-chemistry based companies • Research • Government	• Energy consumers • Retailers/module manufacturers • Policy makers • Investors/developers	• Wind turbine manufacturers • Developers of wind farms • Suppliers of components and services • Government	• Government • General public discourses • In some areas: service providers, manufactures of equipment
- **Relation to energy sector incumbents**	• Integrated, overlap • Same technology suppliers as fossil fuel plants	• Little connection • Natural gas actors	• Little connection, little interest • Exception: a few energy companies	• From opposition to union & accept (regime change) • Some incumbents are now developers	• Double role • Obligation to ensure societal eff. improvm. (government agreement)
Maturity:					
- **Application**	Widespread	No. Demos. Niche use (auxiliary power)	Limited, significant increase since 2010. Late mover	Widespread	Widespread in some sub-fields; considerable variation
- **Industrial networks**	Some, relatively mature Continuation of networks from fossil regime	A little. Research-industry Immature	Scattered, unstable Niches (power electronics, PV materials) A few manufactrs. of modules	Mature – Industrial cluster International companies Hub, test centres	Varies between sub-fields. In many cases well-developed.

Compared to this, the biomass energy and wind innovation systems have reached a considerable degree of maturity and there is widespread market application of the technologies. Though more than 70% of the

[1] Source: Energinet.dk.

energy production and consumption in Denmark are based on fossil fuels, the use of renewable energy technologies have increased considerably in the recent decades. Renewable energy constitutes around 27% of the total energy consumption (compared to 2,7% in 1980 and 10% in 2000).[2] Biomass energy and wind energy account for by far the bulk of this, with biomass energy being around three times as big an area as wind energy. In the period from 2010 to 2015, the share of wind energy has increased significantly faster (14% a year in average in the period 2009-2014) than biomass energy that has stagnated. Around 40% of the electricity now stems from wind energy.

The energy efficiency innovation system in general has significant emphasis on market application and real-life implementations of the new energy efficiency solutions. A considerable degree of maturity with respect to application and establishment of industrial networks appear in some fields, but there is considerable variation between the individual areas of energy efficiency solutions.

The study shows that there are important differences in the relationships between the five innovation systems and the incumbents of the energy sector. This is despite the fact that all five areas are present in the dialogue between policy makers and the energy sector. The character and the degree of the integration with the energy sector regime vary considerably. The wind energy area has for a number of years met strong resistance from leading energy sector actors and incumbents. The central actors for the development of the innovation system have been industrial companies in the manufacturing industry and, especially in the early years, networks of engaged citizens, local communities/cooperatives and NGOs. The role of existing energy sector incumbents has however changed considerably over the latest 1-2 decades from a situation of being in opposition to a situation of accept and integration of wind power in the strategies and development plans of the incumbents and the energy sector in general. Some of the energy companies developed their activity fields and now also appear as developers of wind farms. The major energy company Dong Energy is now among the leading international developers of offshore wind farms. Hence, wind power has moved from being inferior to a core area of the energy sector. Change on regime level has occurred.

Compared to this, energy companies and other energy sector incumbents have been centrally involved in the development of the biomass innovation system all the time. Though policy demands are a central driving force of the bioenergy developments and the drive for the changes does not stem primarily from within the existing energy regime, there are a considerable integration and overlap in the actor landscapes of the prevailing fossil fuel oriented regime and the bioenergy area. The changes are in many cases made in connection to existing heat and power plants and embedded organizationally in the energy sector incumbents. The biomass innovation system is developing in the context of the energy regime and as changes made at the incumbents, rather than, as is seen in the wind areas, as changes made primarily outside the existing regime and elsewhere than at the energy sector incumbents and then later on further integrated in the regime.

The overlap between the biomass innovation system and the existing regime goes further than the energy companies and general energy sector actors. It also concerns technology suppliers and knowhow. Though there are other actors appearing, a number of the companies, e.g., plant designers, suppliers of plant equipment and knowhow are the same as used for fossil fuel plants. Moreover, the biomass technology to a high degree relies on the same infrastructure for energy distribution and the same locations and often also buildings and facilities as the fossil based heat and power plants. Also on this point, the bioenergy innovation system is more thoroughly embedded in the existing energy sector than wind energy where considerable new infrastructure must be created for the transmission of the energy.

[2] Source: Danish Energy Agency 2015, Energy statistics.

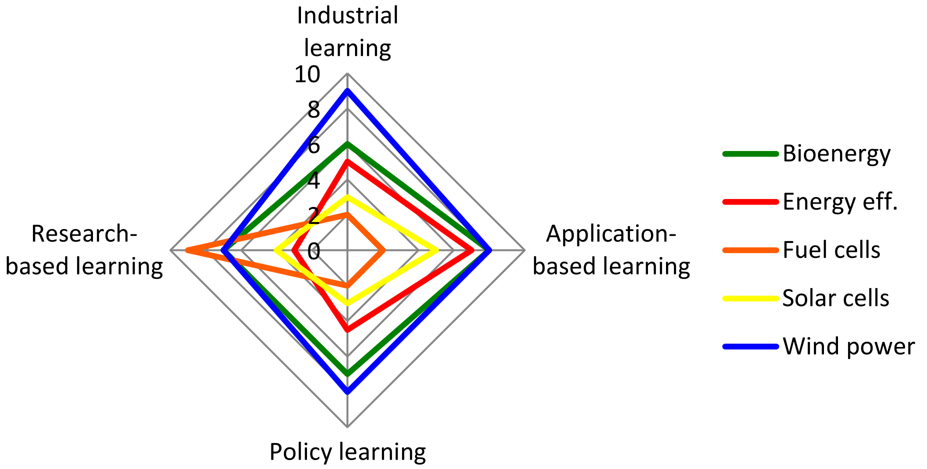
The role of the energy sector incumbents in the solar cells and fuel cells innovation systems is smaller and to a considerable extent more passive than within bioenergy and wind power. In the fuel cell area, incumbents from the gas sector actors appear, but the leading actors in the innovation system are primarily physics-chemistry based companies and research institutions and a limited number of suppliers of small, specialized off-grid or auxiliary energy units. In addition, development companies and local authorities that demonstrate hydrogen technology and infrastructure appear. The other areas in general encompass a broader set of actors than the fuel cell area. In the solar cells area, a few energy companies have actively supported activities, but most energy sector incumbents are more or less passive. The actor landscape is instead characterized primarily by energy consumers, community-oriented NGOs and importers and manufacturers of PV modules. In the recent years, a number of investors and developers of solar farms also appeared.

Within the innovation system on energy efficiency technology, the energy sector incumbents have a double role: the energy sector incumbents are at the same time as they sell energy obliged to ensure significant energy savings in society. This obligation is established through a governmental agreement with the sector. Many energy companies interact with industry and other consumers on energy efficiency improvements. In all five innovation systems policy makers and governmental support are central for the developments. This appears as one of the common denominators of the innovation systems that otherwise in general show huge differences.

Patterns of learning

A sum up of the results of the analyses of learning patterns is shown in Figure 2. The learning patterns in the biomass and wind energy innovation systems show a relatively high degree of both application-/ market-based learning and research-based learning, while the industrial learning is a degree lower in the bioenergy area and there is not developed as many new value chain elements and as many new technical sub-systems, infrastructure elements, business models and roles as within wind energy. The policy learning has moreover been considerable in these areas.

Figure 1: Patterns of knowledge development and learning in five energy technology areas. Assessment on scales from 1 to 10, compensated for differences in size of the areas.



The energy efficiency and solar cells innovation systems both have most emphasis on application-based learning, though it could have been higher with a more ambitious and, in the solar cell area, more consistent and strategically focused market formation effort from policy side. The emphasis on research-based learning is relatively low. The industrial learning is relatively low in the solar cells innovation system in general. Though some module manufacturers exist and some specialized niches and technological competences are developed, e.g., within power electronics and specialized cell materials, the solutions implemented in Denmark are primarily imported. The ambitions in the market formation efforts for example concerning more specialized and higher quality solutions, e.g., with respect to integration in buildings and local prosumer energy systems, could have been higher.

The learning pattern that deviates most from the others is the pattern of the fuel cell innovation system that for a number of years have had a strong emphasis on research-based learning and where only a limited amount of application-based and industrial learning have occurred. The market formation efforts and policy learning in general is also low in the area. The support has primarily consisted in R&D funding and tax exemption on hydrogen cars.

The learning patterns are to some degree results of strategic prioritizations by the actors coalitions centrally involved in the innovation systems and by the public programmes supporting them. They are not just passively created and a 'natural' results of the nature of the technologies or the state of their development. They could have been shaped differently and maybe more efficiently on some points. This might have ended up with other strengths and outcomes of the innovation systems. For example could industrial and research based learning within biomass energy have had a larger weight on biotech and biochemistry actors than have been the case, and energy efficiency could have had a higher weight on also research as supplement to the application based learning. Moreover, the strong research emphasis in the learning in the fuel cell area could have been less pronounced.

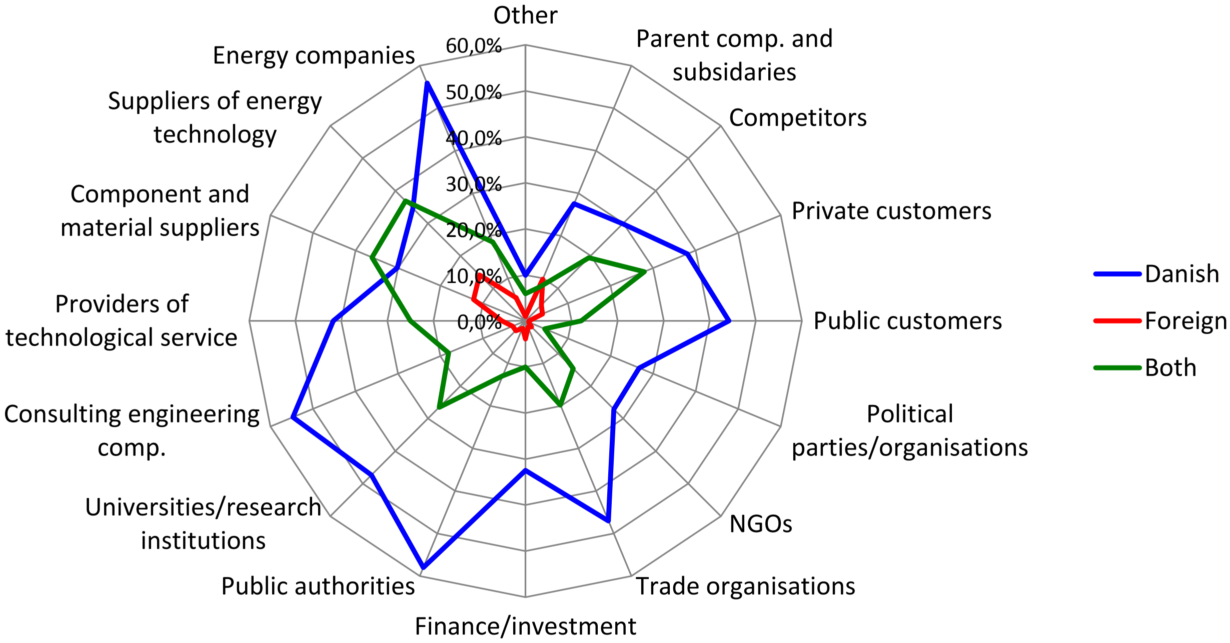
Domestic and international relations

The study's investigation of network and interaction patterns and the role of international relations led to a number of interesting results. The basic assumption behind innovation system studies in general on country-specific level, that there is extensive and complex interaction between actors internally in the country is confirmed. Most actors have interaction and networks with many domestic partners in relation to the energy innovation activities. Though there do appear international interaction and networks as well, the amount of international interaction and the number of international partners are significantly smaller. In Figure 2, the share of actors that have international (foreign) cooperation partners or primarily domestic partners, or both, within different categories of partners is shown. It is seen that within all categories of partner actors, it is the domestic Danish cooperation that appears most frequently, in many cases several times as frequent as international cooperation.

The categories where foreign partners appear most often relative to domestic partners are the categories of industrial suppliers of components and materials and suppliers of energy technologies as such, but also in these categories the domestic connections are the most frequent. This confirms that the domestic level is more significant for the total systemic interplay in the innovation systems than the international.

In parallel to domestic market formation, the role of technology exports to foreign market for the five innovation systems is indicated in Table 2. In all areas there appear some technology exports and the international dimension also in this way do have some influence on the energy innovation systems. There are huge differences however. The exports within solar cells and fuel cells appear as components or small niche areas rather than general energy system solutions. The export is relatively little compared to the other areas.

Figure 2: Cooperation pattern: National versus international partners of Danish energy innovation actors in 2014-2016. N=384. Note: In addition to the categorization of actors from energy companies to political organisations (from '11' to '4' o'clock, anticlockwise), another, parallel categorization also appears (firm-focused value-chain perspective).



The opposite is the case in the wind energy innovation system. It is significantly influenced by drive from exports of solutions to foreign markets in Europe as well as other continents. By far the majority of the wind turbines and equipment and services produced are installed in foreign countries. The strong wind technology exports have in the recent years constituted in the order of 3-4% of the total Danish exports and is hence of considerable importance for the societal economy as such, including creation of employment. This fact has led to additional legitimacy to the wind energy area as well as to clean energy technology and green growth in general. A number of originally Danish companies are now present in a number of countries around the globe and have to a smaller or larger degree become multi-national companies. In addition to manufacturers of wind turbines also developers of wind farms as mentioned have activities abroad.

Still, the domestic activities and the interaction between a high number of specialized expertise areas within the country play a central and important role. The strong industrial cluster that the area constitutes attracts wind technology manufacturers from other parts of the world to establish activities in Denmark. The domestic market concerning onshore wind installation has been a weaker driving force than earlier, however there have been considerable developments of offshore wind farms in the recent years. The learning from these projects play an important role for the development of the wind energy innovation system in general and for the competitive and leading international position a number of Danish companies have reached in this strategically important sub-area.

The exports in the biomass energy area have developed and are considerable, but smaller than in the wind area. Heat and power plants and components for these constitute an important part of this. Also on this point, the innovation system for biomass energy reflects the connection with the fossil fuel regime and builds on competences and industrial networks that originate from fossil fuel based systems. In addition advanced physics-chemistry and biotech process technologies e.g. concerning combustion techniques and treatment of materials constitute a part of the exports from the biomass energy innovation system. In total, the role of the innovative drive from the foreign markets is important, but not as central as it is in the wind energy area.

Table 2: Market drive and assessment of weaknesses of the innovation systems.

	Biomass energy	Fuel cells	Solar cells	Wind power	Energy efficiency
Domestic market drive and market formation	• Policy-driven utilization of national bio and waste resources • Recent years, increasing import of biomass (wood products) • Tariff/tax support	• Very little • Demo H2 fuel stations and cars • Tax exception for H2 cars	• Little • Shifting support schemes; net-metering • Stop-go tendency	• Some • Offshore development; stagnation of onshore • Multitude of policy efforts • Tariff support decreased	• Consumer demand, discourse of efficn. • Energy taxes • EU follower in most consumer product areas
Export drive	Some; heat and power plants, and adv. physics-chemistry and biotech process	Little; niche uses	A little, in niches – not least German market	Strong export World leading companies; onshore and offshore wind Global markets Developers abroad	In some areas only (e.g. insulation, control systems, pumps, district heating)
Weaknesses	• Strong focus on implementation – less on innovation • Top-down more than bottom-up	• Little applicat. based learning • Research bias • Separate activit. on FC and H2	• Scattered, disconnected • Stop-go policy w. little strategic edge • Poor integration in building sector	• Few • Less onshore home market	• Little market formation and guidance of search in specific areas • Little funding for research

In the energy efficiency area there appear considerable exports in some areas, but there are also many of the supported solutions and specific areas of efficiency where no or very little exports appear and where the solutions implemented in the Danish market primarily are based on imported goods. Together with the in many instances relatively passive follower role of specific policy efforts, that seldom go further than EU policy and EU directives define as market forming regulation, the general agreement with the energy sector incumbents on that they have a main responsibility of energy savings in society in general imply that specific market formation efforts from national policy and the guidance of search and legitimation of specific areas of energy efficiency is largely absent. The market formation from public side primarily consists in the general cross-going energy taxes.

Conclusions and discussion

Despite the common context in Danish energy and innovation policy and Danish society in general, the study has shown that the innovation systems with respect to the five energy technologies differ considerably. The study has confirmed that to understand the transition processes towards sustainability through an innovation system perspective it is needed to address individual technology areas and not just the energy sector as such. Despite this, the study has also shown that attention to the relationship between the individual technology areas and the existing energy sector regime and incumbents is an important factor. Different patterns of this are observed. Regime changes in the energy sector take time; decades rather than years. Around 40 years after the oil crises and nuclear struggles in the 1970s and 80s, the renewable energy technologies of wind and bioenergy have become integrated centrally in the prevailing regime.

The learning patterns differ significantly between the technology areas and show varying degree of coordination and strategic strengths. Moreover, there is variation in how the sustainability dimension is appearing in the different areas and with which consistency and level of ambition. All areas are highly influenced by public policy developments. Though an increase in maturity has appeared in some of the areas over the latest decades, there are important challenges and opportunities for improvements in all areas. A number of new challenges have appeared along with the increase in maturity.

For example, in the bioenergy area an increasing dependency on imported biomaterial (wood) is seen. The degree of self-supply is lowering and there is less attention to specialized innovation based on domestically available biomass surplus products. Amongst other things for this reason, it is increasingly contested whether biomass energy is a sustainable energy form, when it reaches the volume it has today.

In the wind energy area, an increasing public resistance has appeared along with the widespread installation of wind turbines and the considerable areas in the landscape (on shore and at sea) they occupy. Though there still is considerable general support of wind energy in society, the not-in-my-backyard effect is significant and a barrier. Another challenge that comes with the increasing maturity of the wind energy area and the considerable export is that a strategic innovative edge cannot be ensured 'just' by support of domestic market application and public R&D funding. In addition, the fluctuation of the wind energy is a considerable challenge when more than 40% of electricity produced by wind. It requires substantial, additional efforts of infrastructure developments and flexibility creation in the electricity systems.

Despite internationalization and open economies, the national and domestic level is still of significant importance for the developments. The study confirms that the national, domestic level is of significant importance for the energy innovation systems. Though there do appear many international relations from the actors in the Danish innovation systems, the domestic relations are more frequent and significant. In the discussion of global and national technological innovation systems the present results support the 'multi-scalar' TIS with cohesive innovation systems in individual countries with relatively weak overlap between the countries (Binz et al. 2014) rather than a completely internationalized TIS with no country-internal cohesion or a global TIS with cohesion both internally and internationally and strong overlap between the country specific systems. To some extent, the solar cells innovation system in Denmark can be seen as rather a part of an international solar cells innovation system than a system in Denmark, with the considerable import of cells to Denmark and exports of specialized components and materials. Within Denmark, the innovation system is scattered and disconnected and works in efficiently. Still we see that activities and efforts within the country, e.g. policy efforts and consumer engagement, are of central importance for the development of the area in Denmark and for whether solar cells shall play a larger role in the transition processes towards sustainability in the country or not. The challenge is to make the activities and interplay more systemically connected in order to ensure that synergies to a higher degree can appear.

The use of the conceptualization of learning types from general innovation system scholars in combination with the technology-specific innovation system framework led to further emphasis and nuances on industrial learning and application-based learning from market formations. As transformative science, the conceptual framework of innovation systems has proven useful. The study has led to suggestions of specific new governance efforts in the individual technology areas as well as some overall recommendations. Dialogue with policy makers as well as industry actors and other stakeholders in the field has been carried out about the results. The conceptualization of different types of knowledge and learning activities also proved useful in this dialogue.

Acknowledgement

The work behind this paper received funding from Innovation Fund Denmark and the Danish Council for Strategic Research, the Programme Commission on Sustainable Energy and Environment through EIS - Strategic research alliance for Energy Innovation Systems and their dynamics.

References

Andreasen, Kristian Peter; Sovacool, Benjamin K 2015: Hydrogen technological innovation systems in practice: comparing Danish and American approaches to fuel cell development, Journal of Cleaner Production, 94, pp. 359-368

Bergek, A. and Jacobsson, S. 2003: The emergence of a growth industry: a comparative analysis of the German, Dutch and Swedish wind turbine industries. In: Metcalfe, J.S. and Cantner, U (eds.): Change, Transformation and Development: Schumpeterian Perspectives. Heidelberg: Physica/Springer

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S. and Rickne, A., 2008, 'Analyzing the functional dynamics of technological innovation systems: A scheme of analysis', Research Policy, 37(3), 407-429

Bergek, Anna; Hekkert, Marko; Jacobsson, Staffan; Markard, Jochen; Sandén, Björn; Truffer, Bernhard 2015: Technological innovation systems in contexts: Conceptualizing contextual structures and interaction dynamics, in Environmental Innovation and Societal Transitions, 16, pp. 51-64

Berkhout, F. 2005: Technological regimes, environmental performance and innovation systems: Tracing the links, in Weber K.M. & Jens Hemmelskamp (eds.) (2005): Towards Environmental Innovation Systems, Heidelberg: Springer, pp. 57-80

Binz, Christian; Truffer, Bernhard; Coenen, Lars 2014: Why space matters in technological innovation systems-Mapping global knowledge dynamics of membrane bioreactor technology, in Research Policy, 43, 1, pp. 138-155

Christensen, J.L., Gregersen, B. Johnson, B. Lundvall, B.-Å., Tomlinson, M. 2008: A NSI in transition? Denmark, in Edquist and Hommen (eds.): Small country innovation systems: Globalization, change and policy in Asia and Europe, Edward Elgar Publishing

Gallagher, K.S., Grübler, A., Kuhl. L, Nemet, G. and Wilson, C, 2012: The Energy Technology Innovation System, in Annual Review of Environment and Resources, 37:137–62

Garud, R. & Karnoe, P. 2003: Bricolage versus breakthrough: Distributed and embedded agency in technological entrepreneurship, Research Policy, 32, pp. 277–300.

Geels, F.W., 2011, 'The multi-level perspective on sustainability transitions: Responses to seven criticisms', Environmental Innovation and Societal Transitions, 1(1), 24-40

Gregersen, Birgitte; Johnson, Björn 2009: A policy learning perspective on developing sustainable energy technologies, in Argumenta Oeconomica, 23, 2, pp. 9-33

Hekkert, M., Suurs, R.A.A., Negro, S.O., Kuhlmann, S., Smits, R.E.H.M., 2007: Functions of innovation systems: A new approach for analysing technological change. Technological Forecasting and Social Change 74, 413-432.

Jacobsson, S. and Bergek, A., 2004, 'Transforming the energy sector: The evolution of technological systems in renewable energy', Industrial and Corporate Change, 13(5), 815-849

Jacobsson, Staffan; Karltorp, Kersti 2013: Mechanisms blocking the dynamics of the European offshore wind energy innovation system - Challenges for policy intervention, Energy Policy, 63, 1182-1195

Jensen, M. B., Johnson, B., Lorenz, E., & Lundvall, B. Å. (2007): Forms of knowledge and modes of innovation. Research policy, 36(5), 680-693.

Kamp, Linda M 2008: Socio-technical analysis of the introduction of wind power in the Netherlands and Denmark, International Journal of Environmental Technology and Management, Volume 9, Issue 2-3, pp. 276-293

Kemp, R, J. Schot and R. Hoogma (1998), 'Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management', Technology Analysis and Strategic Management, 10(2), 175-196

Lundvall, B.-Å. (ed.), 1992: National systems of innovation: towards a theory of innovation and interactive learning. Pinter Publishers, London.

Negro, S.O., Alkemade, F., Hekkert M.P. 2012: Why does renewable energy diffuse so slowly? A review of innovation system problems, in Renewable and Sustainable Energy Reviews, 16, 3836-3846

Quitzow, Rainer 2015: Dynamics of a policy-driven market: The co-evolution of technological innovation systems for solar photovoltaics in China and Germany, Environmental Innovation and Societal Transitions, 17, pp. 126-148

Raven, R.P.J.M., K.H. Gregersen 2007: Biogas plants in Denmark: successes and setbacks, in Renewable and Sustainable Energy Reviews, Volume 11, Issue 1, January 2007, Pages 116–132

Raven, R.P.J.M. & Geels, F.W. (2010). Socio-cognitive evolution in niche development: comparative analysis of biogas development in Denmark and the Netherlands (1973-2004). Technovation, 30(2), 87-99

Truffer B., Markard, J., Binz, C. and Jacobsson, S. 2012: A literature review on Energy Innovation Systems. Structure of an emerging scholarly field and its future research directions, EIS report, radar paper, Lyngby: Strategic research alliance for Energy Innovation Systems and their dynamics, www.eis-all.dk

Vasseur, Véronique; Kemp, René 2011: The role of policy in the evolution of technological innovation systems for photovoltaic power in Germany and the Netherlands, International Journal of Technology, Policy and Management, 11, Issue 3-4, pp. 307-327

Wieczoreka, A.J., Marko P. Hekkert, Lars Coenen, Robert Harmsen 2015: Broadening the national focus in technological innovation system analysis: The case of offshore wind, in Environmental Innovation and Societal Transitions 14 (2015) 128–148

10 lines about the author:

Mads Borup is senior researcher and associate professor at the Technology and Innovation Management division at the Technical University of Denmark, Department of Management Engineering. He has 15 years of experience with studies and analyses of energy technology development and energy sector change towards sustainability. Within the general fields of innovation studies and STS studies he has worked with the analytical-conceptual perspectives of innovation systems, sustainable consumption and production systems, green technology foresight, and the role of expectations in science and technology innovation. Moreover he has worked with user and consumer oriented technology development and research. He has a master degree in engineering with specialization in technology assessment and technology management and a PhD degree in social studies of science, technology and society. He is experienced with stakeholder dialogue and policy advice on levels of countries, sectors, industries, and the Nordic and EU levels.