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Technological learning in offshore wind energy: Different roles of the government

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Abstract

Offshore wind energy is a promising source of renewable electricity, even though its current costs prevent large-scale implementation. Technological learning has improved the technology and its economic performance already, and could result in significant further improvements. This study investigates how technological learning takes place in offshore wind energy and how technological learning is related to different policy regimes. Offshore wind energy developments in Denmark and the United Kingdom have been analysed with a technology-specific innovation systems approach. The results reveal that the dominant forms of learning are learning by doing and learning by using. At the same time, learning by interacting is crucial to achieve the necessary binding elements in the technology-specific innovation system. Generally, most learning processes were performed by self-organizing entities. However, sometimes cultural and technical barriers occurred, excluding component suppliers and knowledge institutes from the innovation system. Danish policies successfully anticipated these barriers and removed them; therefore, the Danish policies can be characterized as pro-active. British policies shaped stable conditions for learning only; therefore, they can be characterized as active. In the future, barriers could hinder learning by interacting between the oil and gas industry, the offshore wind industry and academia. Based on this study, we suggest national and international policy makers to design long-term policies to anticipate these barriers, in order to contribute to technological learning.

Keywords: Offshore wind energy; Technological learning; Innovation system

1. Introduction

Wind energy is a renewable energy source and therefore can contribute to a more sustainable energy supply. A problem associated with traditional onshore wind energy is lack of area for the production of clean electricity. In densely populated countries, the visual impact and sound of turbines hinders the society's accepting of a larger scale implementation of onshore wind energy (Redlinger et al., 2001). Harvesting wind energy offshore can be a solution to this problem and can bring us a step closer towards a sustainable electricity supply. From a global perspective, especially in the densely populated countries around the North Sea, the offshore wind resource in shallow waters is enormous. The United Kingdom, France, Germany, the Netherlands and Denmark together have enough technical potential to accommodate 114 GW of offshore wind energy (CA-OWEE, 2001).

The main barriers to the successful implementation of offshore wind energy are its currently high costs (Verrips et al., 2005). The benefits of an offshore wind project do not always outweigh the costs yet. However, as Junginger (2005) points out, technological learning in the recent past has improved the economics of offshore projects significantly, and it is likely to continue doing so in the future. This makes technological learning an interesting phenomena for society and policy makers, as it could change the outlook for offshore wind energy as a contribution to a sustainable electricity supply.

There is already significant knowledge about technological learning from other studies. Experience curve theory shows how the costs of technology generally decrease with its implementation (BCG, 1968). At the same time,

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discontinuities—e.g. because of radical innovations or unforeseen circumstances—can seriously disturb a ride down the experience curve (IEA, 2000) and make learning trajectories unpredictable (Kash and Rycroft, 2002). In a number of industries these discontinuities have been explained by finding out in detail how technological learning takes place. In other words, the 'black box' of technological learning has been opened by describing which actors learn, about which subjects they learn and how they do so. For onshore wind energy, several studies have attempted to realize this, for instance, Kamp (2002), Klaassen et al. (2005) and Agnolucci (2007).

Offshore wind energy is rather different from onshore wind energy. The accessibility of the installations is far more difficult, the environment is much more harmful due to higher wind speeds, waves and, for instance, salty conditions, the farm size is generally larger, as is the maximum size of the turbines, and the market size is currently still smaller than the onshore market size. Although we have quite some knowledge about how learning takes place in onshore wind energy, for offshore wind energy we are uncertain about how learning processes take place precisely. Scientific data are limited. For instance, Andersen and Drejer (2005) provide a brief insight into how learning takes place in offshore wind energy, focussing mainly on user–supplier relations. In order to explain cost reductions in offshore wind energy, we need to have more information on technological learning also in the industry of offshore wind energy.

The objective of this study is to open the black box of technological learning in offshore wind energy further, to provide insights for policy makers how to stimulate technological learning more effectively and efficiently. This study will answer two main questions. The first question is how technological learning takes place in offshore wind energy. The second question is how policies can foster technological learning. After this introductory section, Section 2 will discuss relevant theories. This results in a case study method in Section 3, proposing a case study of the Danish and British history. Section 4 presents the results from these cases and also discusses future trends. Section 5 describes the conclusions and discussion. Finally, Section 6 provides recommendations.

2. Theory

Innovation and learning are typically activities that take place in systems (Lundvall, 1992). Systems of innovation consist of actors/agents, the relations between them and institutions (Kern, 2000). Actors can be persons as well as organizations. Relations enable interaction between the actors. Institutions are sets of 'common habits, routines, established practices, rules, or laws that regulate the relations and interactions between individuals and groups' (Edquist and Johnson, 1997). One can distinguish systems of innovation on multiple levels. The most appropriate level to focus our analysis on is the level of the technology, since we are interested in the process of innovation in offshore wind energy. Carlsson and Stankiewicz (1991) define a technology-specific innovation system (TSIS) as a network of actors interacting in a specific technology under a particular institutional infrastructure and involved in the generation, diffusion and utilization of technology.

Within the TSIS, a number of concepts are central to our analysis. These are policies, technological learning and performance (Fig. 1). This section will discuss these concepts one by one.

2.1. Policies

A policy is defined as the planning, choices and actions of one or multiple authorities aimed at governing a certain societal development (Rosenthal et al., 1996). In this specific case, the societal development would be the implementation of offshore wind energy while securing a competitive advantage for the national state. We will include both the policy instruments as well as the policy process in our analysis (Hoogerwerf and Herweijer, 1998).

2.2. Technological learning

Technological learning can be regarded as the process in which actors acquire knowledge in order to improve the performance of the TSIS. This definition encompasses three different elements to be specified further.

The first element is the *actors* who are learning. Many parties can be involved in a TSIS. As Smits and Kuhlmann (2004) point out, an innovation system covers the actors who produce knowledge on the supply side, the actors who implement innovation on the demand side, as well as actors who link supply and demand plus actors who support the entire system. To pinpoint what is going on in the TSIS, one needs to describe the learning processes for all these actors precisely, as well as the interaction between these learning processes.

The second element is the *process of knowledge acquisition*, i.e. learning. This can take place in a number of ways. One obvious way of learning is through R&D activities. These activities can range from very fundamental research in universities and knowledge institutes to very practical demonstration projects in small companies. This way of learning can be characterized as learning by searching (Kamp, 2002). Another way of learning takes place during the production of a particular technology. This is often called learning by doing (Arrow, 1962). Next to learning by doing, it is also likely that the utilization of a product provides the user with new knowledge. This learning

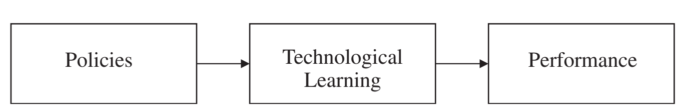

Fig. 1. Conceptual model. Our hypothesis is that policies have an impact on technological learning and that technological learning has, on its turn, an impact on the performance of a TSIS.

process is usually referred to as learning by using (Rosenberg, 1982). A fourth way of learning is through interaction with other actors, also called learning by interacting (Lundvall, 1992). Learning by interacting can take place intentionally via collaboration, but at the same time it can be an undesired result of the 'leakiness of knowledge' (Brown and Duguid, 1998).

The third element is the *subject* of learning. The subject about which is learnt can differ widely. Actors can learn about the technology, like the turbine itself, the foundation or the power transmission system to shore. Also, processes related to the technology can be a subject of learning. Examples of these processes are project planning, installation of the project or operation and maintenance. Another option is that actors learn about one another, or about each other's routines and visions (Leeuwis et al., 2007).

2.3. Performance

The reason for our interest in the phenomena of technological learning is that learning can improve the performance of a TSIS. We express the TSIS performance along a technical, economic and social dimension. Performance is a concept that can be useful to determine the success of a TSIS, also from the viewpoint of policy makers. The difference between performance and success is that success depends on the policy goals set (Åstrand and Neij, 2006), whereas performance describes the functioning of a TSIS in a more objective way. Just like performance, success could be determined along a technical, economic and social dimension, but every policy maker may prefer a different weighing of these dimensions. In this cross-country comparison, we wish to avoid weighing the different dimensions, and therefore choose to use the more objective concept of performance. The different dimensions of performance can be measured as follows.

The *technical performance* is related to the environmental loads on the sites where offshore wind projects are located. The harsher the site conditions, the higher the requirements to the offshore wind technology and the actors acting in the TSIS. The environmental loads on the technology are dependent on many factors like wave height and period, tidal height, wind speeds and turbulence, ice loads, temperature, humidity, etc. In practice, we will approximate the environmental loads in terms of water depth (m) and distance to the shore (km). The water depth is calculated by averaging the mean sea level water depths of the shallowest located turbine with the mean sea level water depth of the deepest located turbine. The distance to the shore is calculated in a similar manner, by averaging the distance to the shore of the closest turbine with the distance to the shore of the farthest turbine.

The *economic performance* is related to the costs of the technology. The more optimized both the technology and the TSIS work, the lower the costs of a project. Two parameters provide a good proxy of the costs, namely investment costs and costs of electricity. The investment costs for a project (€/MW) are relatively easy to determine. They are the same as capital expenditures (CAPEX), which mainly include turbine procurement and construction, support structure fabrication and construction, and grid connection. The costs of electricity for a project (€/MWh) are more confidential and therefore difficult to obtain. However, they give a better estimate of how much the end-user pays for the system. The costs of electricity include investment costs and operational expenditures.

Finally, also the *social performance* of the TSIS is being measured. Social performance is related to the visions of the actors in the TSIS. Visions include two context-relevant elements: (1) the future technology that an actor aims to develop and (2) the trajectory he considers most attractive to develop that technology along (e.g. the crucial problems to be solved first). For proper functioning of a TSIS, it is important that the different actors in the TSIS share common visions, in order to collaborate and together develop the desired technology (Leeuwis et al., 2007). We will therefore investigate which actors are dominant, how they develop visions and up to which degree other actors adhere to these visions.

3. Method

To answer our research questions, we will take a case study approach. The cases of Denmark and the UK have been selected, for a number of reasons. First of all, these countries represent the vast majority of all worldwide realized offshore wind projects. Second, Denmark has been the frontrunner of offshore wind energy, and a large share of the worldwide offshore wind energy industry is located in Denmark. The UK holds the promise to develop into a big market in the future, but hardly has an offshore wind energy industry. Third, both countries have a rather different policy regime, making a comparison very revealing.

Data for this research have been collected in several ways. A literature study has been executed, based on scientific journals and policy documents available at the Dutch Ministry of Economic Affairs (Smit, 2006). Simultaneously, interviews were conducted with Dutch experts in offshore wind energy. Finally, we performed interviews in Denmark with at least one person for every actor category involved in the TSIS. Interviews in the UK were deemed not necessary, since a lot of data were available yet, and the Danish experts were very knowledgeable about the British situation.

3.1. System boundaries

Basically, a TSIS contains all actors, relations and institutions related to the development and implementation of a certain technology. In this paper, we are primarily interested in the development of hardware: turbines, foundations and shore connections as well as installation, operation and maintenance processes related to them.

Table 1
Overview of all realized offshore wind projects in Denmark and the UK until 2007 (WSH, 2007)

Project name	Location	Country	Project completion	Turbine capacity (MW)	Project capacity (MW)
Vindeby	Baltic Sea	Denmark	1991	0,45	5
Tunø Knob	Baltic Sea	Denmark	1995	0,5	5
Blyth	North Sea	United Kingdom	2000	2	4
Middelgrunden	Baltic Sea	Denmark	2001	2	40
Horns Rev	North Sea	Denmark	2002	2	160
Samsø	Baltic Sea	Denmark	2003	2,3	23
Frederikshavn	Baltic Sea	Denmark	2003	2,3 & 3	7,6
Nysted	Baltic Sea	Denmark	2003	2,3	165,6
North Hoyle	Irish Sea	United Kingdom	2003	2	60
Scroby Sands	North Sea	United Kingdom	2004	2	60
Kentish Flats	North Sea	United Kingdom	2005	3	90
Barrow	Irish Sea	United Kingdom	2006	3	90
Beatrice	North Sea	United Kingdom	2007	5	10

Denmark realized a total project capacity of 406.2 MW. In the UK, a total of 314 MW has been completed. All Danish projects have been realized before 2004 and since then, not a single project has been realized anymore.

Therefore, we will not focus on issues like fishery, shipping routes, tourism and ecology, even though we realize that these issues are related to offshore wind energy. However, for technology development and innovation these issues are not of primary importance, so they can be excluded from the TSIS.

Over time, the TSIS as described in this paper developed as follows. The TSIS of offshore wind energy started clearly within (Danish) national boundaries. Over time, however, the TSIS got more and more an international character and no longer can be viewed as a national TSIS or as the sum of national TSIS's. The later developments in offshore wind energy in British waters are an important driving force behind this internationalization of the TSIS.

For the analysis of the cases in Denmark and the UK, it is important to be clear about the boundaries of the two TSIS's. By taking a look at the completed projects in Denmark and the UK, we can clarify which actors, relations and institutions belong to the national Danish TSIS and which belong to a more international TSIS that had a clear foothold in the UK. Actors, relations and institutions that were involved in the development of Danish wind farms have been a part of the Danish TSIS. Actors, relations and institutions involved in the development of British wind projects are part of the more international TSIS we study in the British case. Table 1 provides an overview of all projects realized in both Denmark and the UK.

Table 1 shows that all Danish projects have been developed in the years before 2003. These projects have been the result of a Danish TSIS. Table 1 also displays that in the UK the majority of the projects have been realized after 2003.[1] The development of these projects has been the result of a more international TSIS. With the overview of Table 1, it is possible to identify which specific actors, relations and institutions are typically part of the Danish national TSIS and which elements of the developing international TSIS are of British origin. First, we will focus on actors. Next to national governments, this study distinguishes the following actor categories (Åstrand and Neij, 2006):

- knowledge institutes,
- turbine manufacturers,
- project operators[2] and
- component suppliers.

Table 2 specifies the most important actors in the TSIS for offshore wind energy. Table 2 further obviously shows that the TSIS in Denmark was built around Danish actors. The TSIS in this phase has a national character and can easily be called a Danish TSIS. Since actors are national, their relations are national as well. Also, institutions like trust and cooperation form in a national context. In contrast to this, the British involvement led to a TSIS with a much more open and international character. A 'British TSIS' does not really exist. Actually, the term 'British' refers mostly to the location of the projects (in British territory) and not so much to the nationality of the actors (which is mixed). The applied technology is for a big part Danish, as most projects use Vestas turbines. Involved knowledge institutes are based across Europe, as are the suppliers of components. Only some project operators have a British origin. To put it differently, the involvement of the British authorities in the offshore wind energy business was a clear step into the further development of a more international offshore wind energy TSIS. This is displayed in Fig. 2.

[1]In Section 4.3, we will come back on the reason why the UK did not see so much development before 2003.

[2]This category contains project developers, turbine owners and utilities.

Table 2
Important actors involved in the TSIS for offshore wind energy, with their nation of origin in brackets (DK = Denmark, NL = The Netherlands, DE = Germany, GR = Greece, UK = United Kingdom, CA = Canada, US = United States)

	Knowledge institutes	Turbine manufacturers	Project operators	Component suppliers
Denmark	Risø (DK)	Bonus (DK) Vestas (DK)	Elsam (DK) Energi E2 (DK)	Big role for Wind Power Hub (DK)[a]
United Kingdom	a.o.[b] Risø (DK) ECN (NL) ISET (DE) CRES (GR)	Vestas (DK) Repower (DE)	Shell (UK/NL) Npower (UK) E.ON (DE) Centrica (UK) Dong (DK) Talisman (CA)	a.o. Wind Power Hub (DK) KBR (US) MPI (UK)

[a]The Danish Wind Power Hub is a network of closely linked suppliers, located in Denmark (Dannemand Andersen, 2006)
[b]This is just an overview of the most important knowledge institutes. Here, the members of the European Academy of Wind Energy have been displayed.

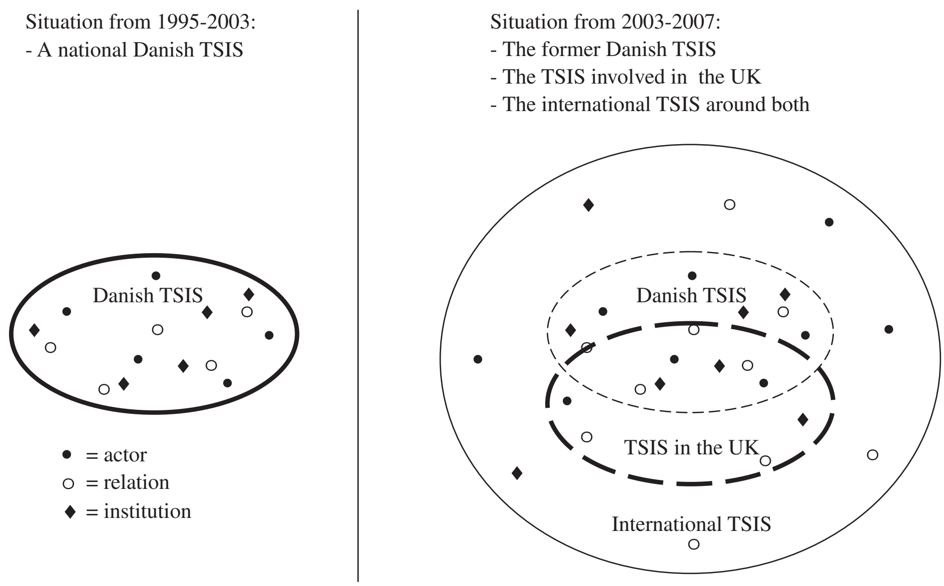

Fig. 2. The relation between the national Danish TSIS and the open and international TSIS in the UK.

4. Results

This section consists of three sub-sections. We will start with describing the performance of the TSIS's in Denmark and the UK in Section 4.1. Next, we deal with policies and learning in Denmark and the UK in Sections 4.2 and 4.3, respectively. Finally, based on our observations, we will design an outlook in Section 4.4. This will provide challenges for policies and learning in the future.

4.1. Performance of the TSIS

The performance of the offshore wind energy TSIS is investigated based on the dimensions as discussed in the theory. The technical performance develops as follows. In the first years of experimentation with offshore wind energy in Denmark, which took place until 1995, two wind farms were realized in relatively sheltered conditions. Turbine capacities were relatively small, the waters were shallow, the wave loads were small and the farms were located close to the shore. Later, from 2000 onwards, the technology for offshore wind energy had to meet more challenging circumstances. Projects have been located in harsher conditions, confronting technology developers with more challenging demands. The technical performance indicators for British wind projects show similar scores as for Danish projects. Table 3 shows the development of technical performance in absolute numbers. Refer to Smit (2006) for a more in-depth analysis of the development of technical performance. The economic performance of the TSIS in terms of costs should be treated with care. Costs are always site-, market- and project-specific. However, one can distinguish a clear trend of falling costs, in terms of both CAPEX and costs of electricity. The CAPEX of the first farms in Denmark were almost twice as high as for later projects, even though these later projects were sited in deeper waters, farther offshore. The upscaling of turbines is likely to have played an

Table 3
Technical performance of the TSIS as defined in Section 2.3 over the wind farms as described in Table 1

Period	1991–1995 (Denmark)	2000–2003 (Denmark)	2003–2006 (UK)
Turbine capacity (MW)	<0,5	2–3	2–5
Water depth (m)	< 5	5–15	5–20
Distance to shore (km)	1–5	1–20	1–12

Data derived from WSH (2007).

Table 4
Economic performance of the TSIS as defined in Section 2.3 over the wind farms as described in Table 1

Period	1991–1995 (Denmark)	2000–2003 (Denmark)	2003–2006 (UK)
CAPEX (€/kW)	2300–2700	1200–1700	1500–190
Costs of electricity (€/kWh)	0.07–0.09	0.04–0.08	Not available

Data derived from Junginger (2006).

important role in the decreasing CAPEX. Later, for British projects, the CAPEX reductions have been smaller. Perhaps, this is a result of shortages on the turbine market (BTM, 2006) and the fact that British projects were located in rougher conditions than Danish projects, of which a majority were located in the sheltered Baltic Sea.

In terms of costs of electricity, the decrease is less dramatic than for CAPEX. This can be related to higher service costs due to longer harbour–turbine distances. Also, some unanticipated setbacks (Wind Power Monthly, 2004) have resulted in higher costs for operation and maintenance. For British projects, data on costs of electricity were unfortunately not available. The absolute numbers for the economic performance are displayed in Table 4. Refer to Smit (2006) for a more in-depth analysis of the development of economic performance. The social performance of the TSIS in terms of shared visions is a more qualitative concept. In its very first years from 1991 until 1995, offshore wind power production was mainly a spin-off from onshore wind power production. A very small number of actors were experimenting with the technology in the Danish TSIS: it only concerned turbine manufacturers and project operators (DEA, 1997). The vision of these actors was to develop onshore turbines into offshore machines with only minor adaptation. Furthermore, the actors were concerned about ecological, economical, regulatory and societal issues. As it was uncertain whether offshore wind would be a viable energy source at all, the visions were only weakly articulated, though well-shared among both manufacturers and project operators (DEA, 1997).

After the first wind farms had proved successful, the size of the Danish TSIS grew as offshore wind held the promise of growing very big within a short time span (BTM, 2001). Suppliers of equipment and services as well as knowledge institutes were attracted by the promising future of offshore wind. A hype-like situation arose. Many actors became involved thanks to fear for lagging behind in the development of a new, fruitful technology (Hjelmsted, 2006). In order to achieve growth in the industry, actors shared the vision to upscale the technology to multi-megawatt machines rapidly (IEA, 2006). Turbine manufacturers took a dominant position in this, like they used to do onshore (De Lange, 2006). Although the turbine manufacturers were the strongest proponents of rapid upscaling development, the vision of upscaling was well-shared among other actors in the Danish TSIS (EWEA, 2005).

The realization of the Horns Rev project in late 2003 formed a turning point in the vision of many actors. After a short period of operation, large setbacks occurred. Turbine failures forced the turbine manufacturer to ship all nacelles back onshore in order to inspect and replace vital components (Wind Power Monthly, 2004; Vestas, 2004b, 2005a). Both the self-esteem of the actors and high growth expectations were adjusted back to a lower level. Danish turbine manufacturers, by that time also active in the UK, probably realized that they had pushed immature technology too early on the market. As a consequence, reliability got more and more emphasis and upscaling moved a bit into the background. This can be seen as an important change in the visions on the further development of offshore wind energy (Cronin, 2006; Beurskens, 2006), which was shared among operators and component suppliers (De Bruijne et al., 2006). Turbine manufacturers released their dominance, as they realized the value of other actors in their efforts to make the system more reliable. Table 5 provides an overview of how the social performance of the TSIS developed over time. Refer to Smit (2006) for a more in-depth analysis of social performance. The previous technical, economic and social indicators have shown how the performance of the TSIS has changed over the years. The indicators point out that the Danish and British cases are strongly connected, as Danish experiences have been implemented in British projects (Vestas, 2004a). Overall, we have witnessed improved performance of the Danish TSIS, directly followed by similar trends in the UK. This supports our statement that the TSIS involved in British projects was developed from the original Danish TSIS.

In the past section, we described the improved performance of the Danish TSIS and, later, the more international TSIS. Next, we aim to explain this improved performance in Danish and British projects. Can the performance be related to technological learning, how did technological learning take place in practice and how can this be related to policies in Denmark and the UK?

4.2. Policies and learning in Denmark

Denmark was the first country where offshore wind energy seriously took off. Initiated by the predecessors of

Table 5
Social performance of the TSIS as defined in Section 2.3 over the wind farms as described in Table 1

Period	1991–1995 (Denmark)	2000–2003 (Denmark)	2003–2006 (UK)
Dominant vision	Develop onshore technology for offshore application	Upscale offshore technology into multi-megawatt machines	Develop offshore technology to make it more reliable
Degree of sharing	Shared among turbine manufacturers and project operators. Other actors not involved	Dominance of turbine manufacturers. Shared among project operators, suppliers, knowledge institutes	No dominance anymore. Shared among all actors

current utilities Elsam and EnergiE2, the experimental projects Vindeby (1991) and Tunø (1995) were realized. After these projects proved successful, the Danish Energy Autority (DEA) envisioned utility-scale projects like Horns Rev (2002) and Nysted (2003) in close collaboration with turbine manufacturers and project operators (DEA, 1997). In parallel with this, a public cooperative drove the development of Middelgrunden (2001) (Wind Power Monthly, 2002). The rise of offshore wind energy in Denmark can be related to strong grassroots in the Danish society (Heymann, 1998).

Next to this societal basis, the support of Danish authorities was important in the development of the TSIS. Especially until 2003, many projects have been realized thanks to an attractive policy regime. However, the 2001 elections changed Danish policies dramatically, leading to a cancellation of three large projects (Roggenkamp, 2003), a more market-based incentive mechanism (DEA, 2005) and a more competitive funding of research (Dannemand Andersen, 2006). As a result, not a single offshore wind project has been constructed in Denmark after 2003 (WSH, 2007). Therefore, we will focus our analysis on policies before 2001 and the related learning processes until 2003.

Until 2001, the DEA, in charge of public tasks related to energy production, supply and consumption, has been supporting learning in the TSIS in two ways. They did this firstly by shaping an attractive environment for technological learning, and secondly by taking away problems that hampered learning processes and could not be solved by the TSIS alone. These two ways will be discussed in more detail below.

The behaviour of the DEA strongly contributed to an attractive environment for learning. More general, Danish policies reduced non-technological risks in the TSIS.

- Market risks were kept small, since the utilities were allowed to freely pass on the additional costs of producing offshore wind electricity onto the end-user in the earliest years of development before energy market liberalization (IEA, 2005).
- The risks for grid connection, like cable fracture, were left entirely with the grid operator and not with the project operator (EWEA and 3E, 2002).
- The regulatory project risks were reduced to a minimum with a one-stop shop concept (EWEA and 3E, 2002; IEA, 2005). All necessary permits, ranging from grid-connection to offshore activities, were to be acquired at the DEA's office.
- Political risks were small, since a social-democratic coalition has been governing for the period 1991–2001, executing a relatively stable environmental regime (IEA, 2005).
- The attitude of the DEA was very cooperative and predictable, enabling utilities to anticipate. Policies were being made in close collaboration with utilities (DEA, 1997; Van Soest and Wevers, 2005). DEA even acted as a policy adviser, pro-actively giving warnings which hurdles utilities needed to worry about (Jørgensen, 2006).
- A platform for learning and experimenting was provided, with subsidies for smaller scale offshore wind projects like Samsø (2003) and Frederikshavn (2002, 2003) and an onshore testing facility at Høvsøre. A platform for learning is a relatively safe environment, in which actors can experiment with the development and implementation of offshore wind technology under realistic market conditions. At the same time, it shapes somewhat sheltered (niche) conditions (Kemp et al., 1998). Samsø and Frederikshavn were relatively small-scale projects, close to portal facilities and easily accessible for operation and maintenance works.

Buen (2007) confirms these findings for onshore wind energy in Denmark. He states that policies had a long-term focus, were in general predictable and comprised both the supply and the demand side of the technology.

Next to contributing to an attractive environment for technological learning, the DEA successfully intervened when the TSIS faced barriers that appeared to seriously hamper learning processes. By pro-actively removing these barriers, the DEA stimulated a proper functioning of the TSIS. The barriers taken away include the following:

- In the first years of development, uncertainties on the viability of offshore wind energy formed a major barrier for component suppliers to get involved in the TSIS. For that reason, the TSIS originally included turbine manufacturers and utilities only. Suppliers did not get involved because of uncertainty about the ecological impact of offshore turbines, uncertainties about the performance of turbines in a humid and salty environment and uncertainty about the costs of electricity

(Wind Power Monthly, 1991, 1993, 1995). The uncertainties imposed a major risk on entering the TSIS for offshore wind energy. In order to reduce the risks, the DEA (1997) supported studies on these themes. Based on the outcomes, component suppliers have become involved in the TSIS.
- After liberalization of the energy market in 1997, utilities Elsam and EnergiE2 changed from good cooperating colleagues to tough competitors. Before liberalization, both parties easily shared experiences and allowed knowledge institutes to use confidential data to perform analyses on. After liberalization the readiness to do so shrank, confronting the research institute Risø with a lack of available data (Jørgensen, 2006). The DEA reacted on this by implementing in its tender conditions a requirement to make data under confidentiality available to Risø (Hjelmsted, 2006).

Having described policies in the previous section, we will now analyse learning processes until 2003. According to innovation theory, three elements need to be investigated, namely (1) the actors that are learning, (2) the way of learning being applied and (3) the subject of learning. These elements will be dealt with one by one.

The actors who are learning have grown steadily in diversity and number. During the first years of development, only turbine manufacturers and utilities have been closely involved in the TSIS. Ten years later, the TSIS included knowledge institutes, suppliers of components, public cooperatives and manufacturers as well as utilities. The growing size of the TSIS can easily be related to the pro-active Danish policy approach taking away barriers for learning. The involvement of component suppliers and knowledge institutes is related to Danish policies.

Danish actors applied multiple ways of learning. The interviewees indicate that they recognize all forms of learning from theory. However, some forms of learning are more dominant than others, and not all types of learning are equally visible in different stages. In offshore wind energy, learning by doing and learning by using are the most frequently applied forms of learning (Lönker, 2005). The substitution of practical experience (e.g. learning by using) by laboratory research (e.g. learning by searching) led to the very expensive maintenance operation with the turbines of Horns Rev as described in Section 4.1. Probably, just like in onshore wind energy, practical small development steps with direct feedback from practice are more efficient than purely research-based forms of learning (Kamp et al., 2004; Garud and Karnøe, 2003). Still, learning by interacting is crucial for actors to get embedded in the TSIS and build up trust. Learning by interacting occurred between knowledge institutes, component suppliers, project operators and turbine manufacturers and is crucial to the success of the Danish wind industry, as the industry describes it as the 'Danish Wind Power Hub' (Dannemand Andersen, 2006). The Danish policies have definitely contributed to the formation of this hub for offshore wind energy.

Furthermore, the subject of learning has become more focussed over the years. Initially, learning had a very broad focus: both ecological issues, economic, regulatory and technical issues were covered (DEA, 1997). Later on, the TSIS focussed more on the technical challenge to upscale the technology to multi-megawatt machines (Hjelmsted, 2006). As Section 4.1 shows, this approach was successful. Still, a major driver behind this has been onshore development, as the upscaling of onshore turbines has shown a parallel trajectory (Dannemand Andersen, 2004), and the installed onshore capacity is still 73 times the offshore capacity (EWEA, 2005).

In summary, we found that policies provided a stable environment for learning until the 2001 elections resulted in actual policies. Besides, the early policies contributed to removing barriers that hamper learning processes. In terms of actors, knowledge acquisition and subject of learning, we have witnessed more and different actors getting involved, dominant learning by doing, using and interacting and, finally, a more focussed subject of learning.

4.3. Policies and learning in the UK

Offshore wind energy took off in the UK with the small project Blyth (2000). Later, the larger projects North Hoyle (2003), Scroby Sands (2004), Kentish Flats (2005) and Barrow (2006) have been developed. Initiatives to realize offshore projects were taken already in 1996 (Wind Power Monthly, 1996), but it took till 2003 before the first large project was installed. Barriers for offshore wind energy in the early days were twofold. Firstly, the electricity market liberalization in 1990 (DTI, 2000) forced utilities to cut costs by reducing risky investments in expensive renewable energy sources. Secondly, a very generic renewable energy stimulation mechanism formed a barrier to the implementation of offshore wind energy projects. Up to 2002 the UK's main renewable energy incentive was the Non Fossil Fuel Obligation (Mitchell, 2000). In this obligation, offshore wind energy had to compete with onshore wind energy and, for instance, electricity from biomass residues, whereas offshore wind energy is a much more immature, technologically risky and therefore more expensive technology (Junginger, 2005). As a result, offshore wind energy did not get a fair chance to reach the commercial market under such a generic subsidy regime.

In 2003, the Non Fossil Fuel Obligation was replaced by a new system, the Renewables Obligation (Simmons & Simmons, 2003). This obligation, combined with renewable certificates and tax credits, requires all utilities to produce a certain percentage of their electricity from sustainable sources. This percentage was 3% in 2003, reaching up to 20% in 2020. In 2002, the policy programme "Future Offshore" was launched, designed specifically to accelerate offshore wind energy development (DTI, 2002). Every offshore wind project was allowed to claim subsidies with a maximum of 16 M€, in addition to the renewable certificates. In this more specific subsidy regime, offshore wind energy developed into an emerging market. British policies with regard to offshore wind energy are coordinated by the Department of Trade and Industries Offshore Renewables Consents Unit (DTI ORCU). With respect to learning, also DTI ORCU's policies have tried to reduce risks in a number of ways:

- The Renewables Obligation takes a long-term perspective, ensuring the income of a producer of renewable electricity over many years, with an expected continuation after 2020.
- DTI ORCU envisions that in 2016, 40% of the UK's wind capacity will be located offshore. This ambition is illustrative for the fact that DTI ORCU takes offshore wind seriously.
- Even though the consenting system is rather strict and complicated, DTI ORCU is very cooperative, providing practical support in acquiring permits. The strict and complicated procedures do not really provide a problem, since in this system the utilities are certain which regulations to comply with ('t Hooft, 2006).

In contrast to Danish policies, British policies did not take away barriers hampering learning processes. Yet, there were some barriers present that policies could have focussed on. British policies focussed on shaping attractive conditions for technological learning only. We will discuss the barriers that policies should have focussed on in the remaining part of this section. Thereby we focus on how learning processes took place based on the theoretical considerations, namely (1) the actors that are learning, (2) the way of learning being applied and (3) the subject of learning.

In terms of the actors who are learning, many Danish actors have been involved in the TSIS driving British projects. The turbine manufacturers was Danish, many suppliers were Danish, as were some knowledge institutes. Besides, some British utilities started operating projects. Next, local British knowledge institutes (e.g. NaREC) received funding but did not get access to valuable information from the projects. The British knowledge institutes did not get really included in the TSIS for offshore wind energy, since project operators were afraid of knowledge leaking away (Westra, 2006). As Kamp et al. (2004) describe for Holland onshore, research and practice developed along their own trajectories, without being framed by—and leading to a—'binding' TSIS. The same goes for the offshore oil and gas industry, from which many lessons can be learned (Van der Tempel, 2002). We will come back on this particular problem in Section 4.4.

Also, in the British case, learning took place in multiple ways. As in the Danish TSIS, the dominant mechanisms appeared to be learning by doing and learning by using. In the international TSIS involved in the UK, project development has advanced steadily since 2003, with one project realized yearly. This trend is likely to continue, with in total 4.1–4.3 GW still in development (WSH, 2007). Obviously, stable incentive mechanisms have provided good opportunities for learning by doing and learning by using. However, in contrast to the Danish development, learning by interacting between British knowledge institutes and project operators occurred only occasionally.

The subject of learning was also different. As the UK represents harsher site conditions than Denmark, the technology had to be adjusted to that. For instance, offshore foundations were mainly made of concrete in the Baltic Sea, as opposed to steel in the Irish and North Sea (Smit, 2007). Also, the focus in turbine development changed, not only due to a harsher environment but also because of the failures at Horns Rev (Vestas, 2004b, 2005a). The primary objective of learning was to make turbines more reliable and able to function with less service under more difficult circumstances (Hjelmsted, 2006; Cronin, 2006; Beurskens, 2006).

In summary, British policies have contributed to learning by shaping an attractive environment for learning. However, some barriers that hampered learning were not removed, since knowledge institutes were not included in the TSIS. In terms of actors, knowledge acquisition and subject of learning, the TSIS involved in British projects has—until 2007—not been as coherent as the Danish TSIS. Learning by interacting has been less important in the UK than in Denmark and the subject of learning changed into making the technology more reliable.

4.4. Policies and learning in the future

Having discussed performance, policies and learning in Denmark and the UK, we will now elaborate future trends. In particular, we are interested in barriers that might hamper learning processes in the future. We focus on the international TSIS for offshore wind energy here. This TSIS involves Danish and British actors, as well as other global offshore turbine manufacturers, project operators, suppliers and knowledge institutes.

One barrier that is still in place from the—rather international—TSIS involved in the UK is the fact that knowledge institutes do not have sufficient access to sensitive data from projects in practice (Westra, 2006). The Danish solution, which requires project operators to share data with knowledge institutes, was implemented in Denmark only. Policy makers in the UK and around may learn from this good practice. Yet, another barrier to resolve—interaction with academia and the oil and gas industry—is relatively young and just emerging. The rest of this section will elaborate on that barrier.

Offshore wind technology is still in its infancy. The realized projects are technologically still very risky (Hjelmsted, 2006) and too expensive (Verrips et al., 2005). Till now, risks and costs could be reduced by technological learning inspired by experiences with onshore wind energy. For instance, learning took place in upscaling the size of turbines, blade aerodynamics or controlling equipment. However, it is unlikely that offshore wind energy will be able to keep taking profit from onshore wind energy. Offshore wind energy will become more independent for the following reasons.

First of all, the technology for offshore wind energy is becoming more complex. The easiest technological improvements have been applied straight away after the first practical experiences in Vindeby and Horns Rev. The required level of understanding to improve the technology was relatively low. Unlike the past, further development will be less straightforward and more complex. In order to keep developing offshore wind energy further, one requires knowledge that stems from a well-developed offshore wind discipline. The level of knowledge will have to increase, since further technological improvements will be less obvious than the previous ones.

Second, the applications of offshore wind energy are becoming more extreme over the years. As it is clear from Section 4.1, the waters become deeper, the distances to shore were longer and the conditions were harsher. The development of Beatrice Windfarm (2006–2007) is a good example of a project under severe environmental conditions in water of 40 m deep (Talisman Energy, 2006). These applications under extreme conditions require fundamentally different characteristics from the technology than onshore applications. For instance, the development of over 5-MW machines is hardly attractive for onshore applications, but is attractive for the offshore market.

The first signals of a more independent TSIS for offshore wind energy are becoming clear already. Knowledge networks, especially for offshore wind energy, have been established (We@Sea), some small companies focus on the offshore market only (e.g. Sway) and big companies conduct their offshore activities in separate business units (Vestas, 2005b).

As onshore wind energy will gradually stop driving offshore development, the international TSIS for offshore wind energy will need to find new sources of knowledge. In order to reduce the risks and costs of offshore projects, one requires competencies in working offshore and reducing the failure sensitivity of turbines. It would be an option to develop these competencies inside the TSIS for offshore wind energy. However, the financial, physical and human resources of the TSIS are relatively limited compared to the enormous volume of the offshore oil and gas industry. The offshore oil and gas industry has been developing over many years and represents an enormous stock of experiences (Meek, 2002), on the one hand for oil and gas production, on the other hand for oil and gas transport. It would take the TSIS for offshore wind energy a very long time to reach the same level. It is therefore far better to look for ways to make use of this existing source of knowledge.

Besides, academia can provide more input to the TSIS than it does currently. The knowledge exchange between research institutes, universities and the industry is not yet optimal (Beurskens, 2006). The connection between these sources of knowledge can be made through learning by interacting. Therefore, future policies should focus on stimulation of interaction between the offshore wind industry, academia and the offshore oil and gas industry (Fig. 3). Through learning by interacting, the actors from the industrial part of the TSIS should get better access to actors in academia and actors in the oil and gas industry. However, there are a couple of barriers hindering this interaction process, which will be described next. Between the offshore wind industry and the more academic expertise on offshore wind energy development, the exchange of know-how is still limited. Even though the actors have good personal relations, only the applied knowledge institutes collaborate intensively with project operators and turbine manufacturers (Beurskens, 2006). The background of this is that both turbine manufacturers and project operators are very afraid of knowledge leaking away to competitors (Hjelmsted, 2006). This seriously hinders academia in conducting research (Van der Tempel, 2006). There is a contradiction between the academic desire to spread knowledge as widely as possible (Van Kuik, 2006) and the attitude to keep knowledge secret in competitive companies (Cronin, 2006). This is the major reason for the barriers between the offshore wind industry and academia. The barriers between the offshore wind industry and the offshore oil and gas industry include the following. First of all, the technology for oil and gas is different from wind technology. Oil and gas projects are usually unique projects involving slow and solid work, the safety demands for manned structures, risks of inflammable and polluting hydrocarbons, very expensive equipment, extremely heavy topsides (Meek, 2002) and dominating wave loads. In contrast to this, in wind energy projects one deals with remarkable effects of repetition, with low safety demands for unmanned structures without high amounts of hydrocarbons, with relatively cheaper equipment, lighter topsides and dominating wind loads.

The second barrier concerns a cultural difference. Historically, the interest of wind energy actors in cooperation with external sectors has been relatively small. The

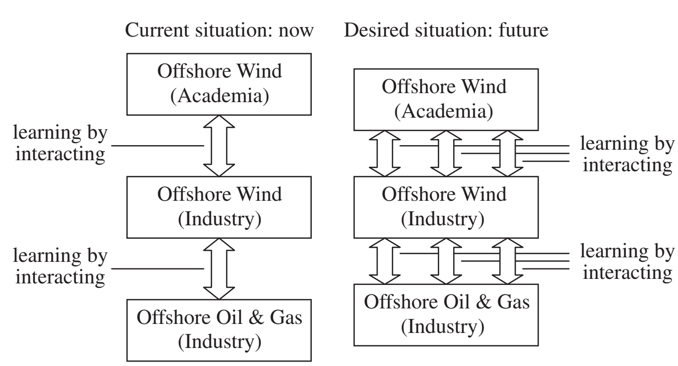

Fig. 3. Different, but potentially related fields of knowledge and how learning by interacting should integrate them. The arrows in the figure represent the amount of interaction between the different fields of knowledge.

success story of the Danish onshore Wind Power Hub is mainly due to its pragmatic approach to experiment gradually towards improved turbine types (Garud and Karnøe, 2003). No big external actors have been involved in this successful approach, so there is a certain reluctance towards involving the offshore industry now. In turn, the offshore industry has its order books filled for many years. The profit margins in the offshore oil and gas industry are much higher than in offshore wind energy, so they do not have an incentive to get active in the TSIS of offshore wind energy (Wind Power Monthly, 2002). Although there are examples of the oil and gas industry learning from offshore wind energy (Schempf, 2003), policy makers should focus their attention on how to make offshore wind a more attractive partner to cooperate with than it is now. In summary, offshore wind energy will need to search for new sources of knowledge, since further technological development will become more complex and onshore wind will stop to drive learning. The most important new sources of knowledge are academia and the offshore oil and gas industry. The barrier that hinders interaction between academia and the offshore wind industry is a different willingness to spread knowledge. The barriers between the offshore oil and gas industry and offshore wind involve technical as well as cultural differences.

5. Conclusion and discussion

In this section, we will return to the research questions. The first question is how technological learning takes place in offshore wind energy. Basically, our observations in Denmark and the UK show that both TSIS's consist of mainly self-organizing entities. Turbine manufacturers, project operators, component suppliers and knowledge institutes have succeeded mainly independently in developing technology towards its current performance. The most important ways of learning were learning by doing and learning by using. Besides, to achieve coherence and collaboration in the TSIS's, learning by interacting has been crucial. In the early years of development, the subject of learning was to adjust onshore technology for offshore applications and to learn about the side effects of offshore wind turbines; later—in line with changes in the dominant vision—the TSIS focussed on upscaling towards multi-megawatt machines and, finally the focus shifted towards the reliability of the technology.

In some respects, the TSIS did not succeed in organizing itself properly. In the earliest years in Denmark, the prospects of offshore wind energy were relatively flimsy, causing component suppliers to feel not attracted to the TSIS. Later, Danish and British knowledge institutes were not allowed access to crucial data for performing their analyses on. These barriers initially hindered the formation of a coherent TSIS. The actors in the TSIS were either not able to remove the barriers or did not have a direct individual interest in removing them.

The second question is how national policies can foster technological learning. We have observed that Danish as well as British policies have fostered technological learning. Both policies succeeded in reducing risks for the learning actors, enabling them to learn by doing and learn by using. Both authorities created stable incentive mechanisms that apparently lasted for many years. This made the actors in the TSIS feel confident that current investments would pay back later and therefore they felt comfortable in learning by doing and learning by using. This conclusion is confirmed by studies on other renewable energy innovation systems, see, for instance, Negro (2007) in biomass digestion. Next to reducing risks with stable policy regimes, especially Danish policies created additional impulses for learning, namely platforms for learning and experimentation. These platforms include near-shore test projects and onshore test sites.

However, there is a fundamental difference between the two countries in the stimulation of learning with respect to the removal of barriers for learning that occurred. Danish policies successfully anticipated on the described struggles within the TSIS. To include component suppliers in the TSIS, the Danish Energy Authority stimulated research into the uncertainties, resolving the barrier hindering suppliers to access the TSIS. Later, Danish authorities obliged project operators to make crucial data available to knowledge institutes under conditions of confidentiality. Both Danish measures delivered the desired result: component suppliers as well as knowledge institutes were able to contribute to an increased performance of the TSIS. Hence, Danish policies pro-actively helped in optimizing the TSIS and for that reason are called *pro-active*.

In contrast to this, British policies did not respond to the barriers hampering learning. Even though it was clear that knowledge institutes did not get involved in the TSIS, British policies left this problem to the knowledge institutes themselves. Neither these institutes, nor the market and the TSIS have been able to resolve this problem. Even though the TSIS in which British projects played a role had a much more international character than the Danish TSIS, the British authorities could have tried to anticipate on the problem of knowledge institutes being excluded. For that reason, British policies are not called pro-active but *active* instead.

From a theoretical perspective, these conclusions have the following implications. For theories on innovation and learning, we can confirm that opening the black box of learning provides us with new insights. The analysis showed that, in order to understand the impact of different policy measures, we need to understand how the TSIS that we are trying to intervene in works. A focus on the different learning actors, different ways of learning and different subjects of learning appeared to be a useful guideline to open the black box. Regarding the substance of our findings, they show that appropriate policy measures are context-specific. The correct policy measures depend on site, time and technology. By this it is clearly shown that it is worthwhile to investigate the required policy measures on a system level.

Nevertheless, the outcomes of this study should be treated with care. There are three issues that limit the reliability. The first concerns the fact that the boundaries of a TSIS are difficult to define. In this study, we have defined a separate Danish TSIS and a more international TSIS in which British projects were also involved. In our analysis, we have studied them as independent cases. We realize that, in practice, the Danish TSIS is strongly connected to the TSIS in the UK and vice versa. Many elements of both systems have an international character. Many involved actors are multinational firms, with employees working on projects in Denmark and the UK simultaneously. Many relations between turbine manufacturers and operators occur both in Denmark and in the UK. And many institutions are not country-specific. For the investigation of the relation between policies, technological learning and performance, a less ambiguous picture would have emerged when the two cases had been more independent. However, the Danish and British cases are not independent, and as a consequence we have to take this complicating factor into account in our analysis.

The second issue concerns the sources of the data this study is based on. Particularly within the analysis of learning, e.g. actors, subjects and processes of learning, we had to base our findings on indirectly written sources and interviews. This can be considered less reliable than scientific articles and it is, for instance, difficult to determine exactly the ratio between learning by searching, doing, using and interacting. In order to constrain this limitation, in-depth interviews have been conducted by the first author on location. These structurally supported the findings of the authors. Next, an extensive literature search has been conducted to verify the assumptions made (Smit, 2006).

The third limitation is the fact that the results of this study are case-specific. International policy makers need to be aware of the phenomena discovered in this study. However, it is uncertain whether these phenomena are equally important in different countries, for different technologies and different points in time. Application of the results requires an in-depth study of the related TSIS in terms of actors, learning processes and subjects of learning. This again shows that, in the domain of innovation, we should be careful in transferring 'best practices' to a different context.

6. Recommendations and outlook

Based on our findings, we can formulate an advice to policy makers, taking into account the remarks in the previous discussion. The first lesson policy makers may take on board from this study is to establish stable and long-term policy regimes in order to stimulate technological learning. This conclusion is in line with the major conclusion of Negro (2007) resulting from her research on the development of a biomass energy TSIS. Both the Danish and British regimes have been relatively successful, thanks to their long-term orientation. This is even more relevant when dealing with an immature, emerging technology. Consenting risks need to be limited, just like market risks or political risks. A good approach providing such a safe environment is to develop a platform for learning and experimenting (Smits and Kuhlmann, 2004), that may act as a realistic but sheltered niche market (Kemp et al., 1998).

The above measures only deal with providing a good environment for technological learning. Policies that only capture these measures can be characterized as *active*. In contrast to this, *pro-active* policies may be necessary to force breakthroughs. Pro-active policies take away barriers that actors in the TSIS cannot solve on their own. In the future, we anticipate two barriers to hinder learning processes: (1) a barrier that hinders academia from interacting with the offshore wind industry and (2) a barrier that limits the interaction between the offshore wind industry and the offshore oil and gas industry. Pro-active policies may focus on the removal of these barriers.

The following policy measures could help removing these barriers. First, obliging project operators and turbine manufacturers to put project information at the disposal of knowledge institutes and universities can stimulate interaction between practice and academia. Next, practical test facilities may function as a bridge between industry and academia. This is where researchers and enterprises could lay a basis for future cooperation. Third, and finally, subsidies can foster the interaction between the offshore oil and gas and the offshore wind industry. Conferences for experience sharing between offshore oil and gas companies and the offshore wind industry could and should be organized. Since both industries nowadays operate in a global environment, this is not a role for national governments only. Especially international policy makers can deliver a major contribution to the development of a more coherent TSIS for offshore wind energy. Simultaneously with conferences, tender proposals with a firm role for offshore companies could be preferred above proposals without such a role. In this way, policies can actively stimulate technological learning in offshore wind energy and deliver the largest contribution to increasing the performance of the TSIS.

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