The Danish wind energy sector's eco-system of research and testing facilities

Academic report from the Danish Centre for Studies in Research and Research Policy, Department of Political Science, Aarhus University

2022

Carter Bloch, Thomas K. Ryan, Mette Falkenberg and Christine Baker

Contents

Executive Summary

Using the wind energy sector in Denmark as a success case, this study investigates dynamics and systemic conditions that have been driving technological innovation within the sector in order to draw lessons that can be transferred to new green technology areas.

The study revolves around seven test and research facilities that are part of the wind energy sector in Denmark: Poul la Cour Tunnel research facility, Center of Reliable Power Electronics (CORPE), Østerild – the National Test Centre for Large Wind Turbines, Blade Test Centre A/S (BLAEST), Lindoe Offshore Renewable Center (LORC), GreenLab Skive and Force Technology.

The key findings are related to the role of political support, funding, a collaborative culture and the role of universities and GTS-institutes. While all the findings for the wind energy sector are also relevant for emerging green technologies, there may also be additional perspectives taking into account the context of early technologies that are not yet commercially viable.

Despite the major challenges of coordinating, fundraising, establishing and operating large-scale testing facilities, the Danish wind energy sector has been able to build an extensive test eco-system which it continues to expand. This system not only supports the development and performance of the Danish wind energy, it also makes it both attractive for firms to keep their R&D operations here or to locate here from abroad.

The state plays a central role in implementing changes that are recommended through consensus by the industry. This includes changes to laws, establishing standards and regulations, coordination among public agencies, availability of funding, and security. Needs are somewhat different for emerging technologies, with greater focus on dispensation and market support, and greater coordination in absence of large industry actors.

Development of new green technologies takes time. Broad support across the political spectrum, as is the case for the wind energy sector, is needed to ensure that the establishment of new technologies can continue across different governments.

The interviewees broadly experience that there is a good interaction with government and that they are willing to aid in the development of the test facilities, albeit a general dissatisfaction with the bureaucracy in terms of time use is voiced.

Megavind and Wind Denmark have played a major role in achieving industry consensus on the strategic planning of large scale investments in testing facilities – similar organisations would be beneficial in these new areas in order to create a shared vision.

Interviewed companies cite a number of advantages with testing facilities in Denmark in comparison with other countries, including capabilities, security and proximity to R&D activities, but they also emphasize that cost is an issue.

Relationships are important here and take time to build up. While great effort is made to form agreements on what can and can't be disclosed, the degree of engagement in both testing and more open collaboration on testing development depends greatly on the strength of relationships.

The wind energy sector is driven by a strong shared vision and collective responsibility for strengthening the Danish innovation eco-system. There is a strong awareness of the mutual benefits of collaboration, also among competitors. Trust and long-term relationships are shaped through collaboration. R&D project funding, university testing facilities and consensus-based decision making all fuel this collaborative culture. Emerging green technologies should not take this as given. There is a need to examine whether conditions are in place to nurture a similar collaborative culture.

The role of R&D funding for collaborations goes beyond financial support; it creates networks, access to facilities and fosters additional private investment. Funding programs help to facilitate R&D collaboration across value chains and between SMEs and universities. Importantly, increased visibility and collaborative relationships through publicly funded projects helps SMEs in securing further business and private investments Project funding thus appears to have a critical role in establishing and growing relationships among actors and shared interest in development work.

Earlier stage applied research funding is also important, yet less available, which potentially may be of even greater importance for emerging technologies.

Creating and maintaining the right conditions for small and medium sized companies (SMEs) is critical for the success of the Danish wind energy sector and for other green technologies. In addition to R&D funding, regulations and exemptions, which often require local-state coordination, reduce barriers and costs, facilitating SMEs' R&D activities.

In the Danish wind energy sector, universities are not just a source of competences and new research results. They also function as a focal point for collaborative work across different actors in the sector. University-run testing facilities connect to industry through the interplay between testing and development activities. GTS-institutes play a key role in certification activities and establishing standards that are critical for sector development. GTS-institutes also have specific competences that often differ from those at universities.

Introduction

Climate goals for 2030 and 2050 place great demands on the development and implementation of green technologies that produce, transport and store energy with lower CO_2 emissions. Governments are stepping up efforts to support the development of a variety of green technologies and Denmark is no exception. In 2020, the Danish Government identified four green missions to be supported by research and innovation policies: carbon capture, climate efficient fuels, climate-friendly agriculture and food production, and reuse and reduction of plastic waste[1].

In 2020, 700 million DKK was earmarked research within the four green missions, at different stages of the research and innovation value chain, as part of in total 2.3 billion DKK in research funding in green technologies. More recently, in 2021, the Government presented more detailed proposals within 14 areas covering increased investments and innovation funding, national and EU standards and regulations, local development and international collaboration[2]. These initiatives stress the need for intensified investments in research and innovation, and in the importance of knowledge exchange and collaboration across different actors. In total, funding support targeted to green research and innovation has increased rapidly from 2020, where a total of 4.4 billion DKK from Danish public and private foundations and the EU Horizon 2020 program was awarded to Danish research and innovation projects[3].

At the same time, there is also a recognition that strong framework conditions need to be created, which include the establishment of an eco-system to support the development and growth of these new technologies. From a broader perspective, Denmark needs to support the creation and growth of innovation eco-systems surrounding these targeted green technologies.

This study is part of the project "Climate ends and means" launched by the Danish Council for Research and Innovation Policy (DFiR), which generally examines whether the public research and innovation system is designed in the best possible way in accordance with the Climate Act's goal of reduced CO_2 emissions.

The Council has chosen wind energy as a case for a well-functioning system of research and testing facilities, which has contributed to the development and implementation of wind technology.

This report presents the results of a study that examines the wind energy sector's eco-system of test and research facilities to shed light on dynamics and systemic conditions that can be transferred to other green technology areas and thus address the aforementioned issues through policy recommendations.

The wind energy sector is an example of a successful innovation eco-system in Denmark. From its early beginnings in the 1970's, the sector has now grown into an established industry that is a world leader. A number of factors lie behind this success, including a strong engineering tradition, favourable market conditions, political support, a strong research environment and extensive collaboration among actors.

Test and development facilities have been and continue to be a crucial part of the innovation eco-system, providing state of the art facilities, performing the vital role of qualified certification, and

[1]https://ufm.dk/publikationer/2020/filer/1-fremtidens-gronne-losninger-strategi-for-investeringer-i-gron.pdf
[2]https://kefm.dk/Media/637751860685972853/Fremtidens%20gr%C3%B8nne%20br%C3%A6ndstoffer.pdf

[3]https://ufm.dk/publikationer/2021/filer/kortlaegning-af-finansiering-af-gron-forskning-og-innovation-i-2020.pdf

serving as a platform for collaboration and development activities.

However, previous success does not mitigate the challenges that the Danish wind energy sector faces. Fierce global competition means that the sector must continually develop in order to stay ahead. The system of test and development facilities is central here and needs to stay at the forefront. In order to accomplish this, strong framework conditions are needed, and conditions that support ongoing and wide-reaching collaboration that can generate new innovative solutions.

The objective of the study is to examine what dynamics drive technological development in the wind energy sector eco-system of test and research facilities, the role of regulatory and institutional framework conditions, and potential lessons for emerging green technologies. It seeks to shed light on the following questions:

- How does cross-sectoral collaboration work and what factors contribute to promoting or preventing collaboration, knowledge sharing and development?
- What role do research and innovation policies (including funding, infrastructure, competition, legislation, rules and standards) play in the development of test and research facilities (technological, economic and societal)?
- What challenges and opportunities do the wind energy sector's test and research facilities face?
- What potentials exist for better interaction and value creation (both technologically, economically and socially)?

As such, the study focuses on both the individual test and research facility and its role in the wind energy sector's eco-system.

Both the story of how the Danish wind energy sector and how it functions has developed over time and continues to develop now can provide valuable lessons for the support of other green technologies.

Section 1 reviews the development of the Danish wind energy sector since its beginnings in the 1970's. Section 2 describes the interview study behind this report, while section 3 characterizes the different types of testing facilities that support the Danish wind energy sector. Section 4 examines the role of framework conditions while section 5 examines the conditions for R&D collaboration both within the industry and with universities and GTS-institutes. Section 6 looks briefly at development activities within two related technology areas: power electronics and reliability, and Power-to-X. Section 7 summarizes the main results from the study and concludes with perspectives on the relevance of the study findings for emerging green technologies.

1.0 Background

1.1/ Innovation eco-systems

This section looks back at the origins of the innovation eco-system around the Danish wind energy sector. An innovation eco-system can be defined as: "*the evolving set of actors, activities, and artifacts, and the institutions and relations, including complementary and substitute relations that are important for the innovative performance of an actor or a population of actors.*" (Granstrand and Holgersson, 2020). Artifacts can include a number of technological and non-technological resources, while actors include manufacturers, suppliers and sub-suppliers, users, universities and research and technology organisations, and political and regulatory institutions.

The eco-system within Danish wind energy has evolved in a number of ways since its early beginnings in the 1970s, where the roles of a number of different factors can be highlighted as key junctures in its development. Karnøe and Garud (2012) point out that many of the competences, institutions, regulations and markets surrounding wind energy did not exist beforehand; they emerged due to a number of factors, where decisions and developments had a great influence on the overall evolution of the sector.

1.2/ Early years of Danish wind turbines

The story behind Danish wind energy can at least be traced back to the 1970s, where early grassroots wind turbine entrepreneurs suddenly experienced a dramatic increase in the relative profitability of wind energy due to the energy crises in 1973 and 1979 (Graversen 2017, Karnøe 1991). This, combined with requirements that power companies were required to connect wind energy to power grids, and government subsidies that were linked to local test certification at Risø (now part of DTU) created strong, favourable conditions for local production and development in Denmark (Graversen 2017). This certification established a key role for test facilities, which has evolved and greatly expanded over the years.

These developments gave Danish production a technological advantage that they were able to capitalise on in the 1980s with the strong increase in demand for wind turbines in California, where Danish producers were main suppliers.

Policy has played a key role throughout. Examples are the regulation that required power companies to install wind turbines in 1986 and the large role given to wind turbines in the energy plan in 1996 and in subsequent plans. It is also worth noting that in this initial period, innovation policy as we know it today had not yet taken form. Hence, the main policy interventions before 2000 are regulations, subsidies and investments in research institutions.

1.3/ Danish wind energy sector since 2000

In the last 20 years, the sector has increasingly taken on the characteristics of an established industry. This is particularly notable in the important role of large manufacturers (OEMs) that have extensive R&D capacity and are able to financially support the development of capabilities in the Danish system.

The value-chain and system of suppliers has also undergone change in the last 20 years (Megavind, 2020b). As the industry has grown, broader layers of suppliers have developed. Initially, these were suppliers that were directly under a single OEM. However, over time the system has become more complex. OEMs have increasingly outsourced many activities in order to narrow their focus on core competences. Hence, suppliers and sub-suppliers have taken on a larger role and have acted more independently in supplying to more than one OEM or supplier. This increased complexity has implications for policy, knowledge exchange and for the role of test and development facilities.

The role of universities and GTS-institutes has also evolved. These institutions were central actors in technology development during the 1980s and 1990s. However, in the last 20 years, OEMs, with their large R&D departments, have become less dependent on universities. A key contribution from public research is still its focus on novelty and longer-term developments, which are the topic of collaborations with OEMs.

In contrast to OEMs, the increasing number of small and medium sized companies (SME), that are part of the wind energy sector, typically do not have the same R&D capabilities, or the financial capacity to engage in collaborations with public partners. This creates an important role for innovation policy to support and create strong conditions for the development of SMEs. This includes necessary local conditions for SMEs to operate and conduct R&D, funding to facilitate public-private R&D collaborations involving SMEs, and to ensure that user models make SMEs' access to test and development facilities feasible.

1.4/ The role of test facilities

The role of test and development facilities has grown substantially since the early years of the sector. These facilities had an initial role of providing certification and standardisation for wind turbine production. While this was a vital role for the industry, it was narrower in scope than it is today. The system of test facilities is now much more complex and extensive, covering all components and different stages of the development process. If one surveys the current testing landscape, many of the key testing and development facilities are quite new (for example, CORPE, Østerild, the National Wind Tunnel, BLAEST and LORC). The breadth of facilities is now very wide-reaching but is also undergoing continuous renewal to accommodate increases in size. This is particularly the case for BLAEST, LORC and prototype testing platforms (e.g. Østerild), where planning is underway to establish a new testing site with capacity for wind turbines up to 400 meters in height.

A key meeting point for interaction between public and private partners has been through testing, hence efforts to foster increased public-private collaboration have revolved around test and development facilities.

While the Danish wind energy sector is widely recognized as a success, there is an important need for remaining at the forefront – Denmark needs to have state of the art test facilities, which requires the right capacities, equipment and competences. Collaboration and supportive framework conditions are needed to achieve this.

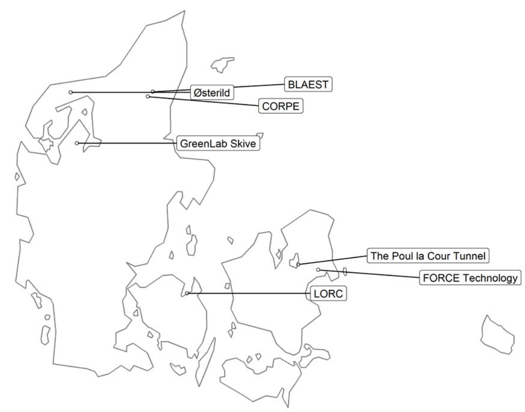
"To maintain Denmark's position as a global hub for wind energy, it is essential that Danish-based companies continue to have access to relevant state-of-the-art test and demonstration facilities and test competencies." (Megavind, 2020a)

2.0 About the study

Using the wind energy sector in Denmark as a success case, this study investigates dynamics and systemic conditions that have been driving technological innovation within the sector in order to draw lessons that can be transferred to new green technology areas. The wind energy sector has been selected as a success case due to its broad sectoral cooperation, well-functioning eco-system, and complete system of test and research facilities across the value chain. As a part of the DFiR project "Climate ends and means", which examines whether the public research and innovation system is optimally organized to meet the climate goals for 2030 and 2050, this study contributes with an understanding of the impact of collaboration dynamics and framework conditions around test and research facilities for the wind energy sector.

The study is based on 23 interviews with different actors from within the wind energy sector as well as extensive desk research outlining the eco-system of the wind energy sector and historical events critical to the sector's development and success. The study revolves around seven test and research facilities that are part of the wind energy sector in Denmark. While the establishment of other structures, such as sub-stations and cables, has also been important for the complete function of the wind energy network, this study focuses on the development and use of test facilities for wind turbines.

The facilities were selected based on their diverse ownership structures, Technology Readiness Levels (TRL), role in the value chain and geographical location in order to cover framework conditions and cooperation across the eco-system. The facilities included in the study are BLAEST, CORPE, FORCE Technology, Greenlab Skive, LORC, the Poul la Cour Tunnel and Østerild.



BLAEST
Blade Test Centre A/S (BLAEST) specialises in full scale structural testing of wind turbine blades. Previously a part of the RISØ National Laboratory, BLAEST was founded in 2005 by FORCE Technology, the RISØ National Laboratory, and Det Norske Veritas as a private company operating on commercial terms. Today, BLAEST's test facilities are located at rented facilities at the port of Aalborg. BLAEST is DANAK-accredited to perform fatigue tests, static proof tests and external tests[4], and test reports from BLAEST are used as documentation for type approval. BLAEST does not have the authorisation to certify type approvals.

CORPE
In 2012, Center of Reliable Power Electronics (CORPE) was established at Aalborg University with funding from the Danish Council for Strategic Research and four core industry partners Danfoss Power Electronics, Grundfos Management, KK Wind Solutions, and Vestas Wind Systems. CORPE focuses its research on reliability in power electronics and offers tests on the longevity of power electronic systems and components[5].

[4] https://blaest.com/
[5] https://www.corpe.et.aau.dk/

FORCE Technology

As an Approved Technological Service (GTS) Institute, FORCE Technology is a private non-profit company. The GTS institutes' mission is to foster Danish innovation and competitiveness by supporting companies' use of new technology. GTS institutes operate both on commercial and non-commercial terms, and are supported by government funds of around 300 million DKK annually[6]. Since its founding in 1940, FORCE Technology has moved beyond its initial scope of certifying steam boiler welds and is now active in a range of different areas, including the wind energy sector and new technology areas such as Power-to-X. FORCE Technology provides various testing services for the wind energy sector and covers the entire value chain[7].

GreenLab Skive

GreenLab is an industrial park dedicated to the development of green energy. GreenLab generates sustainable energy that is supplied to the businesses located in the industrial park, towards the development of electrofuels and other green products[8]. The industrial park itself is privately funded, while many of the projects within the park are publicly funded. As a part of GreenLab Skive, GreenLab Skive Wind was initiated in 2016, aiming to establish a wind farm. The facility is hence not involved in the actual development and testing of wind turbines[9].

LORC

Founded by offshore renewable energy actors in 2009, Lindoe Offshore Renewable Center (LORC) is located at the former Maersk shipyard near Munkebo. The facility is operated as a non-profit private foundation and provides different types of tests under simulated conditions on commercial terms, including climatic testing of structures, systems, and components, and Highly Accelerated Lifetime Testing of drive-train components and full-scale nacelles[10]. The test facilities are partly funded by customers, loans and public funding.

The Poul la Cour Tunnel (National Wind Tunnel)

The Poul la Cour Tunnel research facility at Technical University of Denmark (DTU) RISØ Campus specialises in aerodynamics and aeroacoustics. Funded by Technical University of Denmark, Region of Zealand and the Danish Research and Innovation Agency in 2012, the wind tunnel was completed in 2018[11]. The wind tunnel engages in research activities as well as supports industrial testing of wind turbines on commercial terms.

Østerild

Østerild – the National Test Centre for Large Wind Turbines is a full-scale test facility of offshore wind turbines on land. To ensure the optimal wind conditions for testing large wind turbines, the test centre was established on the west coast of Denmark in 2012 based on a national law. In 2019, the test facility was expanded from seven to nine test stands with the possibility to test wind turbines up to 330 metres on five of the nine stands. Two test stands are owned by Vestas Wind Systems and two by Siemens Gamesa Renewable Energy. The remaining five test stands are owned and operated by DTU and rented by industry[12].

Table 1 below shows key characteristics for each facility.

Study participants

As a part of the study, 23 semi-structured interviews have been conducted during October and November 2021. All interviewees were selected based on their expertise and experience within the field of wind and actors with strategic roles from all seven selected test and research facilities, as well as some of their users and collaborators, have been selected to ensure that framework conditions and collaboration were covered from different perspectives. Interviewees include managers and staff from the included facilities, board members from the included facilities, representatives of OEMs and suppliers and industry representatives.

---

[6] https://gts-net.dk/
[7] https://forcetechnology.com/
[8] https://www.greenlabskive.dk/
[9] http://greenlabskivevind.dk/DK.aspx
[10] https://www.lorc.dk/
[11] https://www.plct.dk/
[12] https://windenergy.dtu.dk/test-centers/oesterild

All interviews were centred around collaboration dynamics and framework conditions and followed an interview guide which was adapted to the varying roles of interviewees and quality checked throughout data collection. The interviews were conducted online and ranged from 30-50 minutes in length. All interviews were recorded and transcribed, and thereafter coded and analysed through a two-stage process. The first stage was used to identify key themes of the interviews, drawing in part on the interview guide, and the second stage was used to code and analyse the material across the identified themes.

Table 1. Key characteristics of the testing and research facilities

	Purpose	Year est.	Financing establishment	Financial model	Example of/main users	Ownership type
BLAEST	Testing	2005	Private company owned by DTU, DNV and Force Technology	Commercial	OEM, SME, university and GTS	Private company
CORPE	Research and testing	2012	Public/Private (Danish Strategic Research Council and private companies)	Public/Commercial	OEM, SME, other industry, university	University
FORCE Technology	Testing	1940	GTS-institute established in 1940	Public/Commercial	OEM, SME, other industry, university	GTS-institute
GreenLab Skive	Research and testing	2016	Private company with investments from public and private actors	Public/commercial	OEM, SME, other industry, university, GTS	Private company
LORC	Testing	2009	Non-profit commercial foundation, investment from both public and private sources	Commercial	OEM	Private
The Poul la Cour Tunnel	Research and testing	2018	Public, funded by DTU and regional and state government	Public/Commercial	OEM, SME, university and GTS	University
Østerild	Testing	2012	Public based on investments from private companies	Commercial	OEM	Private/ university

3.0 Differences across facilities

In this section, we look more closely at the types of testing facilities and the differences in conditions and challenges that they face. As argued above, a key component of the innovation eco-system for the Danish wind energy sector is the broad range of test and development facilities that is both state of the art and covers all aspects related to wind turbines. The widespread view from the interviews is that Denmark is at the forefront globally in terms of testing facilities for the wind energy sector.

"We are very fortunate with the conditions we have here in Denmark. There are few other places where you can do it the same way. Test sites exist in other places around the world, but they usually have limitations that make them less relevant. That is, you cannot set up big enough turbines. Or if you look at testing of nacelles like at LORC. Here, LORC has without comparison the largest test facilities. Here, we are better off than most."

At the same time, the interviews emphasized the need for continued development, and also pointed out a number of challenges linked to the test facilities.

"The success of our sector can be compared to a three-legged stool, where one leg is competencies, "..." the second leg is we need some primary production in Denmark close to the competencies which means the development centres and the universities. And finally, we need the required test facilities close to where the strong innovation departments are. And if all legs are not strong, the Danish sector will tumble over. We are under a lot of pressure to move everything abroad. "..." and we can get it done cheaper abroad. If we want to maintain a strong industry with 30.000 jobs in Denmark, we need to make sure that those three legs are strong."

There are a number of different types of facilities in the Danish system, both in terms of ownership structure and level of development or technological readiness levels (TRL). Each of these types can be seen as suited to the specific purpose and testing needs, whether it is prototypes, blades, nacelles, materials, components or other aspects. At the same time, the interviews point out the different challenges that each facility has in balancing state of the art testing services with ongoing development of the facility and its staff competences. Many of these issues and challenges are also discussed below concerning both the role of framework conditions and conditions for R&D collaboration.

The first type is facilities located at and run by universities. This includes both permanent facilities such as the National Wind Tunnel and centers such as CORPE, which were established through a multi-year grant and are dependent on further grants to continue work over time. These facilities typically operate at a lower TRL, involving R&D and to some extent exploratory research. These facilities hence are active both in providing testing services and in conducting research, where we will see below that there can be strong synergies between testing and research activities. University run facilities are also typically those that are most relevant for smaller companies that are part of the overall value chain, whereas OEMs utilize all types of facilities. Finally, being located in universities, these facilities in many cases also function as important training grounds for engineering students.

The second type is GTS-institutes. GTS-institutes have a unique role in the Danish innovation system, providing knowledge-intensive services to businesses and acting as a bridge between universities and industry. GTS-institutes provide a broad range of services to a number of industries, including the wind energy sector. They have a key role within certification and standards, and have also developed specialized skills within selected areas that complement the competences offered by universities.

The third type is commercial facilities. Both BLAEST and LORC were established as a response to needs created by the rapidly increasing scale of wind turbines. The increasing size of wind turbines meant that very large testing facilities were needed for testing blades and nacelles, with a business model that was capable of securing the large investments and income needed to establish and maintain the facility. Commercial facilities are solely devoted to testing, which is not possible for university-run facilities.

Given the unique conditions surrounding them, we argue that prototype testing platforms such as Høvsøre and Østerild form a separate, fourth type. Due to their nature, these facilities are university run (by DTU), but like commercial facilities, their sole purpose is to conduct testing. In order to establish both these two test sites, along with plans for a third test site that can accommodate wind turbines up to 400 meters in height, new laws were needed to allow for the expropriation of land for the sites. Both the process leading up to the establishment of these sites and the model for how they are run have been key subjects for discussion during the interviews. These, along with the funding model, where all costs were covered by OEMs, make this a separate type of facility with its own issues.

As is already apparent from the descriptions above, there are good rationales for both having commercial and non-commercial facilities, however both have different strengths and different challenges.

Facilities located at universities create the opportunity for interaction between testing and research, and potentially also with education. This is particularly important for creating a space for R&D and innovation activities that can also involve different actors across the value chain.

"We have income on the commercial side in the laboratory which benefits the research and development track "…" And via the commercial activities, we also have good contact to the companies that can generate new research and development activities, and which can improve the technology in the field."

"The problem is that in a commercial test centre there is a big time pressure, while spending more time evaluating the observed results is allowed in a test centre conducting research. This is also a prerequisite for the innovation that is important to achieve the goals that the parliament has set. So, we need non-commercial test facilities where innovation can be created."

However, the other side of this interplay is that it creates concerns of confidentiality and secrecy, which are not an issue for some collaborations but decisive for others. The opposite is the case for commercial facilities, where there are no problems with confidentiality, though less room and time for long-term research and development.

Business models of course differ across facilities. University facilities often have gone to great efforts to secure initial funding to establish the facility, where the National Wind Tunnel is a case in point. However, these facilities need to generate sufficient income from testing to cover expenses, at the same time maintaining research activities (which can be supported in part by funding grants). Hence, there is a balance and challenge here, though our impression from respondents is that it is a business model that functions.

GTS-institutes main purpose is to promote the use of new knowledge and technologies by private companies, and hence their main activity is to provide technological services to companies, also within certification and testing. Force Technology provides a number of services to the wind energy sector and thus cannot be seen as a single facility. While Force Technology's primary focus is on commercial activities, it participates in R&D collaborations and is able to apply for R&D funding from a government funding pool earmarked to GTS-institutes.

Commercial facilities such as BLAEST and LORC need to focus on commercial testing activities in order to generate sufficient income to support the large investments behind these facilities.

The prototype testing sites are a special case. Respondents note for example that Østerild is unique both in its size capabilities and in wind conditions, which are able to emulate offshore conditions better than other locations abroad. However, a number of respondents note the challenges and difficulties in the implementation process (which is now ongoing for a new test site) and also frictions with the current business model. Key points, which will be discussed in greater detail below, are both the pricing, access to platforms, and sharing of what is very sensitive data.

4.0 Framework conditions

In this section, we describe how framework conditions are relevant to the establishment, adaptation and operation of test facilities in the Danish wind energy sector.

The importance of different framework conditions to test facilities depends on the type of facility. As noted above, the size and height requirements in test sites such as Østerild and Høvsøre mean that expropriation and national construction laws are required, while the establishment of large-scale facilities at DTU and LORC was dependent on the availability of funding and/or loans. A common aspect for all large facilities is the need for coordination among a diverse set of actors in the eco-system.

In this section, we review the ways in which laws and regulations, the political process, national funding and lending arrangements are relevant to the establishment, adaptation and operation of test facilities in the Danish wind energy sector. Some areas are mainly relevant to the establishment of test facilities, while others have implications for operational aspects or when technological or market developments necessitate updates and adaptations to test sites and facilities.

Historically, the local market for wind energy was closely linked to the building of a testing eco-system in Denmark. The early demand propelled the creation of a wind energy hub in Denmark. Large turbine manufacturers and public research were established and developed during a period of high domestic demand for wind energy. Currently, the dominating demand is now global, however, the competencies and manufacturers are situated in and to some degree bound to Denmark.

Over the last 20 years, even more advanced test and research facilities have been established and two of the world's largest wind turbine manufacturers have a large part of their operations in Denmark.

While similar facilities exist globally, they are to a higher degree dispersed throughout the globe, Denmark is unique in that a diverse set of facilities needed in the research and development eco-system are located within a very small geographic area. As exemplified by the citation below, this concentration of test and research facilities and engineering skills and competencies contribute to making Denmark a highly competitive hub for wind energy research and development. Moreover, a continued development and expansion of the testing eco-system is a core driver for large turbine manufacturers to maintain their headquarters and R&D departments in Denmark.

"We are mainly dependent on the test and demonstration facilities, because we cannot do much about it ourselves. Due to our size "…" we can easily attract people from other countries to come to Denmark to work for us. The testing system we cannot do anything about unless there is political goodwill. The production we control ourselves."

There are a number of challenges for the establishment of test facilities. The interviewees express that overall, one of the major issues is that the time from identification of need to a functioning and valuable facility takes several years and many resources. Closely related to this, the size of investments is very large and therefore require coordination and commitments from many partners. The time horizon from conception to completion was for example 5-6 years for Høvsøre and Østerild, and 8 years for the National Wind Tunnel.

Despite the major challenges of coordinating, fundraising, establishing and operating large-scale test facilities, the Danish wind energy sector has been able to build an extensive testing ecosystem, which it continues to expand. The interviewees point to a number of important aspects and mechanisms that have contributed to the successful establishment of a range of facilities.

In the sections below, we introduce the different framework conditions that affect test capacity building both in terms of placing restrictions and barriers and in terms of solutions and beneficial structures.

4.1/ The appropriate site and political accommodation

When the identification of a need and solution is formulated, a site for a test-facility has to be found. Test facilities for wind turbine prototypes are particularly challenging, as they often require a substantial area. Not only do appropriate sites have to be identified, but often national government has to be involved because there is a need to expropriate. In other circumstances local government has to provide special approvals and exceptions.

The process of obtaining approval for the establishment of a test site is very long and rough. As a number of interviewees explain, processes involve a number of steps from determining needs, identifying suitable sites and obtaining political approval, where it typically takes 2, 3 or even 4 years to obtain the right permissions and removal of restrictions and registration.

Furthermore, the process will often need to be repeated to accommodate future developments. For example, the building law for Høvsøre only allowed for a specific height of wind turbines, which would require a new law to allow for greater heights. A new site (Østerild) had to be built going through the same process once again. As of today, the height development means that a third test site is on the agenda that will allow for even taller wind turbines.

Other types of test facilities may not require the expropriation of acres of land, but still require large areas, where buildings and sites can accommodate the logistical issues of transporting large wind turbine parts to and from the facility. Moreover, there are often special requirements as to access to specific facilities. This was the case for the privately owned BLAEST, who have established themselves in the port of Aalborg and emphasize the partnership with the port as a central framework condition for the test facility.

"We just say what we need, and they will find a solution. They are really proactive and there's no doubt that they are supportive of the wind turbine industry and really, they have been successful in their work on blades."

Moreover, others require special permissions for the business case to be realistic. GreenLab Skive is an example of how the regulatory authorities provided an exemption to regulations concerning connection to the electrical power grid in order to provide cost reductions to promote development activities, and how the local government supported the initiative through building permits and other permissions.

"The Danish Energy Agency has given us a regulatory test zone permit, which gives us a 10-year exemption from the Electricity Supply Act. That means that GreenLab can test new technologies and test innovative business models in practice with the purpose of relieving the overloaded electrical grid and contribute to a faster transition to non-fossil fuels. The Danish Energy Agency has chosen to collaborate with us so that we can test new solutions and knowledge share together."

In almost all cases, political goodwill and reciprocal partnerships between test facilities and local government are mentioned as important facilitators of well-functioning test facilities.

The need for special permits and appropriation means that local and national politicians have to be willing to spend political capital on aiding in this process. Even though there is a very strong dependency on political goodwill, the interviewees broadly experience that there is a good interaction with government and that they are willing to aid in the development of the testing eco-system, albeit a general dissatisfaction with the bureaucracy in terms of time use is voiced.

"It all takes time, right? And perhaps that's ok, then it will be done properly. But it can still feel like an barrier. That you must constantly wait for the [policy-makers] to meet, a law proposal to be drafted and a hearing and whatever else and then we can talk about it in three years. "..." Now we have started a process for a new test facility and it probably won't be ready for another 5 years. But all sorts of things are done during those 5 years. It's because the process takes 5 years. It's not that the process isn't ongoing, it just takes time."

In a number of interviews, the former prime minister of Denmark, Poul Nyrup Rasmussen, was mentioned as an example during his time as chairman of the board for LORC of how political capital can be very useful for implementing large projects. Moreover, the examples of GreenLab and BLAEST show that there are large benefits to having goodwill with local actors. Finally, in the construction of test sites Østerild, Høvsøre and the 3rd test site, interviewees mention how it is fundamental that politicians can see the rationale behind the projects and back it up through expropriation and building laws.

"We are ready to act, the industry is ready to act. So, it is political goodwill that we are dependent on, and it is a little scary that you rely on political goodwill in that way. The rest we can do something about ourselves. But the political goodwill is more difficult to control. Luckily, the politicians have said it is a good idea... including test centre three."

4.2/ Raising funding and the funding landscape

Raising capital for large scale test and research facilities requires the ability to build a business case that can convince lenders of the likelihood of commercial viability. Alternatively, or additionally, a strong case for the scientific value must be made to persuade research funding agencies to provide funding for establishment of test facilities as research infrastructure.

There is no single procedure or source to secure the large sums of money that are needed to establish these large test facilities, hence processes to raise capital are to a certain degree uncoordinated and different in each case. However, key elements are, as mentioned above, political will to support the wind energy sector combined with consensus across the industry that the new or expanded facility is needed.

"During the initial phase, The Research and Innovation Agency wanted us to gather national support. In relation to this we had a lot of work. It was not because it was difficult to find support but more the formulation of the actual project with all its specifications. Based on our discussions, we handed in a report and based on this, the financial support was granted."

Megavind plays a key role in coordinating recommendations from the wind energy sector. Formed in 2006, Megavind is a partnership among actors in the Danish wind energy sector with the goal of charting strategies for the future development of the sector. The partnership has been successful in reaching consensus on a number of strategies, including the development of new test facilities, where many of the group's recommendations have been implemented.

"Our processes are very consensus driven. That means that when Megavind develops a recommendation, you can trust that it is a sector-wide recommendation that has been approved by the entire wind industry. Both sub-suppliers, suppliers, OEM's and developers agree with the content. This can have a beneficial effect, for example on the regulative areas and in legislation processes. That we from the Wind Denmark secretariat can say that this is the opinion of the whole industry and not just a single company."

Gaining funding can be complicated for commercial facilities due to EU competition rules for receiving state support. A number of interviewees perceived that Denmark adheres to these rules more strictly than in other countries, putting Danish facilities at a competitive disadvantage.

"Apart from this, we do not receive any financial support for operation or for investments. Here, we are disadvantaged compared to our competitors abroad, who are driven partly as research organisations and who receive substantial public funding for both operation and capital investments, which are also used for purely commercial testing activities in direct competition with us. It is difficult for us to make an attractive business case when we compete with publicly funded test centres both inside and outside of the EU."

4.3/ Business models and pricing

In addition to the availability of financing, an additional economic parameter is the cost of testing services. Interviewed companies can cite a number of advantages with testing facilities in Denmark, including capabilities, security and proximity to R&D activities, but they also emphasize that cost is an issue. Danish facilities are in competition with other facilities abroad, which may be much cheaper.

"The fact that you can find areas where, when you get up high, it is as if the wind turbines were at sea. And that's what makes it so attractive with Østerild. It's an amazing location because it is almost like having an off-shore wind turbine, when it is at Østerild. "…" And the R&D departments are in Denmark, so the engineers can easily get in a car, head out to Østerild and do the measurements they need to do. That's what's great about Denmark as a location. But if it is too expensive, then the companies will stop using it and find a different location for their wind turbines. They would prefer not to, they like having their R&D departments here, because that is where they are "…" Then they end up deciding; what is the most important? Is it excellent physical facilities? How much does that weigh compared to price? Somewhere along the line, one is greater than the other, and that may shift."

In some cases, when using university based testing facilities, the OEMs are required to allow parts of the test data to be used for research, which they feel can be an issue in terms of secrecy.

Cost is also a key factor concerning SMEs' access to and use of testing and research facilities. Respondents from SMEs stated that their use of facilities took place primarily as part of funded R&D projects, as the costs for using test facilities on their own were typically too high.

4.4/ Coordination and collaborations

Closely related to both funding and political accommodation is the coordination and collaborative capabilities of the actors within and around the wind energy sector. The size of investments and timeline of establishment require coordination between actors that often could be characterized as competitors.

The interviews, however, point to a highly collaborative and coordinating environment. Where actors both bilaterally and through corporate organizations coordinate large investment in test facilities, as it is often seen as a mutually beneficial investment.

Vision and aims for new facilities are often a result of a collaborative effort within the system in which compromises are reached on what is needed. Thus, both research departments, suppliers and OEMs contribute to decision making with regard to what is built and which specifications and instruments there should be. This is true regardless of the ownership structure.

5.0 Collaboration

As mentioned above, the sector has had a history of collaboration among OEMs and universities, where the relation between universities and industry has changed over time from the 1980s and 1990s to today. At the same time, value chains have become much more complex, with OEMs focusing more and more on core technologies and a growing network of suppliers emerging to produce components and take on other activities. The system of testing and development facilities has also grown extensively over time. While an important need for collaboration between OEMs and universities remains, there is now a growing need for collaboration across different actors in the wind energy sector.

Megavind (2015) outlines potential benefits of closer cooperation for both universities/GTS institutes and industry.

Benefits for industry[13]:

- Opportunity for applying the latest research in R&D activities.
- Opportunity to recruit R&D candidates with an updated knowledge.
- For large and small suppliers in particular access to knowledge areas that is not embedded in the company through:
    - Cooperation in R&D projects (shared knowledge (medium/long term).
    - Consultancy services (exclusive knowledge (short/medium term).
- Student projects.
- Development of common industry standards and practices for test and verification based on research results.
- Access to test, validation and demonstration facilities

Benefits for the universities and GTS institutes[14]:

- Funding for research projects through company participation that strengthens research areas.
- Ensures relevant research both in ongoing and new research areas.
- Opportunity for knowledge sharing with industry experts in joint projects.
- Application of research results in commercialised products provides an opportunity for feedback and proves value of research in the industry.
- Opportunity for publications together with the industry.
- Increased interaction with the industry will result in stronger industry involvement in educational activities and increased quality and relevance for students.
- For GTS: Established business model for test and validation of components and processes based on standards and norms

In this section, we review the results and insights from the interview study on the factors that influence collaboration within testing and development and its potential contribution to innovation. Among the key points that emerged from the interviews are:

- Funding plays a key role in bringing partners together on R&D collaboration activities, and is particularly important for SMEs and commercial facilities
- The interplay between testing and development activities has the potential to establish close relationships between companies and universities, to promote collaborative development work, and to help ensure the relevance of university research to the wind energy sector.

[13] Source: Megavind (2015, p. 8)

[14] Source: Megavind (2015, p. 8)

- Longstanding relationships and trust are essential for the value of testing and development collaborations.
- The nature of collaboration is very much different according to the types of partners, whether it is between OEMs, OEMs and universities, involving smaller suppliers or the type of testing facility (commercial or non-commercial). The level of technology development (TRL) is also relevant for the collaboration.

5.1/ The role of funding for collaboration

For many actors, project funding is needed to make collaboration around development work possible. Both universities and the large OEMs engage in R&D collaboration within and outside funded projects, while supplier companies and commercial test facilities are more dependent on funded projects to facilitate collaborations. For this reason, project funding is widely seen as crucial for making broad-based R&D collaborations possible. There are a number of programs, such as EUDP, Innovation Fund Denmark and Innovation Fund Europe, with particular emphasis on the role of EUDP.

"Of course, we are happy to have some of our costs covered through EUDP projects, but it also adds value that we gain access to knowledge, test facilities and partners. Among other things, it is very valuable to gain knowledge through the 15 wind turbine owners who participate in the latest EUDP project. During the first seven years of the company's history, where we had to pay salaries, patent expenses, and rent, we also needed some money to develop and have our products demonstrated on a large scale. The money from EUDP was of course central but it was also an essential reason that we were able to raise 30 million DKK in investor capital."

Funding programs thus help to facilitate R&D collaboration across value chains and between SMEs and universities. Through these funded collaborations, SMEs are able to gain access to test facilities, which would not have been feasible otherwise. These projects involving test facilities also allow SMEs to form connections with other participants, and build on their testing work.

"We would not have built everything we have today if we had not had support from EUDP. And it is not because of the money which flows to companies, DTU, AAU, etc. Through EUDP projects that we have been a part of, we have built close collaborations, among other things we have benefitted from the universities' test facilities. We would not be able to afford to own a test centre or rent a test centre at fully commercial rates."

At the same time, it was pointed out that EUDP is focused on higher TRLs, making it best suited for development and demonstration projects that are led by companies and have a very clearly defined goal. In particular following the structural changes to the research and innovation funding system in 2014 (where among other things, the Strategic Research Council was discontinued), there is a gap for applied work that is at an earlier development stage.

"Under EFP (Energy Research Program) we had a research program which ran for several years. Here, we created milestones year by year, with a frame running over five years. We developed some tools and some generic knowledge which we still use today to a large extent. "…" Such generic tools are difficult to develop under EUDP today."

"To ensure that research has impact and that you are able to do some generic and solid research, I actually believe it would be beneficial to move projects further down in TRL and give universities the possibility to work there too."

5.2/ Conditions for collaboration.

Test and development facilities can, under the right conditions, help to strengthen relations that can be used to engage in more exploratory development work. Testing provides an opportunity for partners to gain familiarity with one another, and can often generate questions that can motivate discussion on how to improve or build on testing procedures.

"We do a lot of testing and a lot on composites and composite material for the wind turbine industry "..." Partly, we of course help the industry with their needs to test material, components and structures. Partly, it generates new income to the laboratory, and partly and perhaps most importantly, we meet the companies at a different level than we normally meet them as a university. Because, traditionally, when we present our research and development ideas, it might be something that takes longer for the companies to implement."

"We have an income on the commercial side in the laboratory which benefits the research and development track "..." And via the commercial activities, we also have good contact to the companies that can generate new research and development activities, and which can improve the technology in the field."

"Obviously, the companies should have their own test facilities to support the ongoing development that we do, "..." but there is also research in asking: How do we become better at understanding the enormous complexity in the solutions that we do here? And that's where collaboration between companies and universities really pays off, when we're able to do it and we have a set-up that enables us to do it together. "

Relationships are important here and take time to build up. While great effort is made to form agreements on what can and can't be disclosed, the degree of engagement in both testing and more open collaboration on testing development depends greatly on the strength of relationships. While there are still dilemmas with this, the ability to work together is viewed as a strength in the Danish model.

"... So, we can collaborate on many things. In fact, it is something that makes the Danish wind energy sector unique worldwide that we know how to talk with each other."

Strong, long-standing relationships are hence cited as a key reason why R&D collaboration has increased, with the perceptions of what areas or technologies are open for collaboration expanding over time. This includes both early stage technologies but also areas where companies have assessed that the gains from collaboration outweigh losses of competitive edge or are considered to be outside the company's core competences.

The following example illustrates the building of a collaborative relationship among competitors:

"Initially we struggled a bit with asking: What kind of collaboration do we want this to be? It took a while before we established the consortium by saying that we could have a joint venture with the universities and that we could get external funding and that sort of thing. It took a while before we found that framework, and then we needed a legal foundation for the collaboration agreement. And that was a bit of an uphill battle as well, that our legal advisors from different companies and universities had to work together to develop an agreement that worked for everyone. It took a while to discuss all those things. Especially about how we would handle confidentiality issues, who has the IP rights that might come out of it and those kinds of things. But I think it's been quite easy, and once we had the first project in place, the next one was easy, because we could just build on what we already had, and the relationships were there and the framework that we had to build was there too, so it has actually worked quite well. "

Differences in goals and perspectives between universities and industry are at the same time what creates potential for gains from collaboration and a barrier to knowledge sharing. While companies want to keep proprietary knowledge to themselves in order to maintain a competitive edge, universities are focused on publication and knowledge spreading. This difference is particularly the case for what companies consider to be their core, product-related technology, where uncertainty about confidentiality can hinder collaboration.

Therefore, many of the collaborative projects the interviewees participated in were often described as pre-competitive, whereas projects close to the core of the manufacturers were stricter in their confidentiality. While firms would use external test facilities, they would do so with strict confidentiality and limited interaction and exchange of information.

"I actually find it positive that you both do commercial work, and thereby have contact with the industry, and that you also ensure that the generated knowledge is translated to good research. It is a constant balance where you need to find out how to weigh the commercial aspect and the research related aspect. But it is an ongoing challenge to do that."

"We are very concerned that knowledge on what is confidential to us slips out. That is, our core technology."

There appears however to be broad recognition across facilities with different goals/perspectives/ownership structures that maintaining confidentiality, when required, is critical for testing facilities and R&D collaboration.

"If a new industry that we have not talked to before comes in, we have some meetings where we both ask questions. [...] in terms of the actual work but also in terms of the general level of service, confidentiality, and the requirements put forward. Even though, we have been working with companies for many years, we still need to write NDAs (non-disclosure agreements), etc., to ensure the confidentiality. This way, the formalities are in place, but the most important thing is that the customers know that we can keep information confidential and that they experience that we can maintain the confidentiality. No information can get to third parties."

"Sometimes we'll say, here we are interested in finding a joint solution. So, then it will not be so secret. We are perfectly capable of doing projects with our competitors. "..." Then there are the projects where we can keep secrets, and obviously it is a dilemma that the same people who work for xxx work for us the next day, or the other way around. "..." We also have some demands for the universities. Other than the NDA, which must be in place, there must also be a degree of awareness amongst the staff. Sometimes it is difficult because the universities have other agendas. They would like to publish as much as possible. Actually, they must publish. It is probably a cultural difference there and we are in the process of discussing how to handle that with the universities. But we will definitely be posing some demands if we are to collaborate on areas close to our core. If we are to invite the universities into our projects more, and they get data from us, then we need to be able to do that."

Other types of testing facilities are more aligned with industries. Both commercial facilities and GTS institutes have a clearer, singular focus on the provision of test services to their customers as opposed to a dual objective of drawing on testing activities to further their research. Hence, at facilities such as LORC and BLAEST or at Force Technology, there is strict confidentiality and there does not appear to be any issues with concerns over secrecy. The sole focus is to perform needed tests on materials or components, with no potential friction due to an extra objective of using results in research or the presence of students (we will discuss the latter below). We also inquired to what extent this confidentiality impedes the ongoing improvement of development methods, and in all cases the response was that there was a broad understanding that general results or learning concerning testing methods could be incorporated and applied in future testing with others.

"It's a balance between general knowledge and very specific knowledge about a customer's product and that is the balancing that we continually try to manage in a set-up like this one. "

Hence, there is a degree of learning by doing that does not appear to be hindered by non-disclosure agreements (NDAs). However, at the same time there is a recognition that this incremental learning was not sufficient to keep at the cutting edge. R&D collaboration is needed to improve their knowledge and competences and stay at the forefront. As noted above, funded projects were cited by commercial facilities and GTS institutes as a key source of their R&D collaborative activities. However, it was also noted that there is limited time at commercial facilities to devote to development activities, for example at a facility such as LORC, where large investments and financing have been secured for the purpose of providing testing to the wind energy sector.

Students also play a role in collaboration and development activities surrounding test facilities and also illustrate some of the issues that need to be navigated. A large number of respondents have emphasized the importance of educating qualified engineers for the wind energy sector and have also argued that there is a need for greater focus on competences within testing[15]. In addition, student master's projects and industrial PhD's can in some cases offer good opportunities to engage in development work concerning testing methods. Both these points indicate benefits of greater involvement of students in testing activities. On the other hand is the issue of security and discretion concerning testing that is confidential, where some respondents have noted that the presence of students at testing facilities can create unease whether confidential data can be adequately protected.

[15] See for example Megavind (2016).

6.0 New Technologies

The development of the wind energy sector also depends on other areas or technologies, where OEMs and suppliers are potentially not the main drivers, even though their development is connected to the wind energy sector and important for its success. In this study, we have touched on two examples: power electronics, where we have focused specifically on reliability and CORPE, and Power-to-X.

6.1/ Power-to-X

Power-to-X (P2X) can be defined as the process by which green electricity is converted to hydrogen, or other products based on hydrogen[16] . It is particularly seen as a solution for sectors where electricity and batteries are not an obvious option, such as in heavy industry and sea and air transport. The process behind P2X first involves electrolysis, where green electricity is used to convert water to hydrogen. The hydrogen can then be used as an energy source, where the hydrogen through a synthesis process is combined with either nitrogen or carbon and forms a number of new P2X fuels.

There is currently a tremendous amount of activity and interest in P2X, though technology in the area is still at a very underdeveloped stage. There are a number of challenges that need to be addressed, and they appear to be highly interdependent – not everything can be resolved at once. Progress has to be made and barriers overcome, but there is also a question of finding the right timing for the development of research and testing facilities, and there needs to be a substantial degree of agility to act on how the system and technology develops.

The Danish government has very recently presented a strategy for the development of Power-to-X[17]. The key items of the strategy are: increased funding to production and innovation investment in P2X, establishing direct electrical connections to P2X systems, reducing tariffs for use of the electricity grid, and working at the EU level to increase demand for green fuels and clear regulations.

P2X is not the primary focus of this study, but can be seen as an example of the new technology areas that can gain insights from the development of the wind energy sector. We have conducted a small number of interviews concerning P2X, using GreenLab Skive as a reference point. While these do not adequately cover the area from a systems perspective, the interviews yield a number of insights on the role of collaboration, framework conditions and testing for the development of P2X.

Given that P2X is still explorative, with great uncertainty attached to development work, it is important that conditions are in place that make testing and development feasible. Two key elements that has made GreenLab Skive possible are a 10 year exemption from regulations that require that electricity is drawn from the established electricity power grid and political support from Skive municipality. GreenLab Skive has thus been able to establish their own 80 megawatt wind turbine park that supplies electricity directly to the industry park, without any tariffs. This allows actors in the park to conduct R&D and testing at much lower costs. An additional objective with this exemption is learning from activities towards the development of a new regulatory model. The support of the municipality was also seen as instrumental in helping to ensure and expedite processes to obtain environmental and building permits to establish the GreenLab Skive facilities.

[16] https://www.danskenergi.dk/fakta-fokus/dansk-energis-power-to-x-partnerskab/power-to-x

[17] https://kefm.dk/Media/637751860733099677/Regeringens%20strategi%20for%20Power-to-X.pdf

"And that's why some of us break some of these ... protective regulations that are in place because we believe things need to be done in a new way. You must combine the sectors and think energy as one. Several people agree with us, politicians and people that work with regulations, they just have a hard time working out what we should do instead. We're not saying that exemptions should be the operating model. What we're saying is that we get this exemption to create a new model, which can then create a new model for how it should be regulated in the future."

In addition to supporting framework conditions that adapt to the needs of the sector, development will depend on research and innovation efforts from both businesses and knowledge institutions. Arguments have been made for both a strengthening and greater coordination of research efforts within P2X[18] .

"P2X is distinctive in that there are not many commercial projects right now. Most of them are publicly funded projects. They are financed by different aid schemes and are often in very explorative phases. That means that if you want to be in P2X right now, you need to be part of a project consortium. The facilities are not built yet, they are only in the planning phases or in the investment phase, so that's where the business is right now."

"Enabling a new business, like P2X, may rely on very particular techno-commercial challenges to be solved, which are normally expressed in cost-performance indicators. The established nationally funded research programs, for example on electrolysis, may be applicable to these challenges but only in part. The residuals, which may be too exclusive to become national research program contenders, are then left to industry, commerce or academia to find other means to address."

There are a number of reasons for this. First, research is essential to contribute to solving the large technological challenges facing the sector. Second, there is also a great need for knowledge transfer to fuel continued progress. A strong presence of universities in the R&D and collaborations helps to secure greater openness, which may be missing due to intense competition among commercial interests.

"The most important thing right now is to connect the value chains and to get it to make sense. And that is actually the hardest thing to do. Over the past two years we have shifted from a mutual interest in proving the technology at a larger scale between companies, to a point where you are really fighting to protect your domain, because it has become commercially interesting to be in the P2X business."

A goal of the business park at GreenLab Skive is to create an environment with both businesses and knowledge institutions in close proximity, thereby fostering collaboration. However, the presence of universities is fairly new, where e.g. DTU has recently opened a research center at GreenLab Skive. Finally, there is an important need for standards, certification and testing facilities, which will likely be very dynamic in response to sector needs. Universities and GTS-institutes have an important role in supporting this development.

"That's probably where we have some challenges: the lack of standards and guidelines, where Denmark wants to be ahead, like we were with wind, where we helped shape the guidelines and standards for the entire industry. One example is in relation to the hydrogen that is produced from electrolysis, where a very conservative standard for hydrogen quality is used, which will be unnecessary in most cases regarding the uses that we are currently seeing for hydrogen."

"One could wish for test facilities for a lot of other things, that is hydrogen, energy storage, and... "..." But we also must be careful not to spread ourselves too thin. So we have not yet made any decisions about it, that it is something you need to do something about."

https://ing.dk/artikel/P2X-strategi-ida-vi-skal-have-viden-ud-siloerne-241186

6.2/ Reliability

Power electronics concerns the conversion of electric energy from one outlet to another, and thus is relevant to both the wind energy sector and a number of other industries and uses. Our focus is more specifically on reliability, as this is what CORPE works with. Reliability essentially has to do with the longevity of a product or a component, to determine the likelihood that it will break down within a certain time period, such as 10 or 25 years. Research in this area seeks to develop advanced models that are able to produce precise estimates of reliability through accelerated tests that can be conducted in a very short period of time.

Our study in particular focuses on the conditions for collaboration to improve this technology. Both for the wind energy sector and for other industries, reliability can be seen as a technology that is of central importance for product performance (and thus also for firm's competitive edge) but is not a core competence for most of the companies involved. Given this, the different actors, some of whom are direct competitors, still found that there were strong benefits to open collaboration.

"Actually, one of the good things in this field is that the companies have realized that this is not an area to compete in. It is something that we can collaborate on. It's know-how, where, if we all get better at working together, we all benefit. "..." You're not too close to their products. "..." So in that way it's been easier to get the companies together and find that it's beneficial to work in these areas."

"We believe that we hold an even stronger position in our collaboration in relation to the real competition, which is not the internal competition between us, but really comes from further afield, perhaps more from the East, where they have several thousand more engineers than we have in Denmark. So, we believe that if we can share our new knowledge and our cumulated knowledge, then we can face the actual threat of competition outside Danish borders. So even though we compete, we are also aware that we need each other, and we benefit from each other, and we can separate daily business from what we in this context call the more pre-competitive and we build knowledge together which is... which we believe is incredibly valuable."

Respondents described how the collaboration was built up over time. Initial arrangements within projects took some time to set up, in particular legal agreements concerning eventual intellectual property rights for research results. However, once established the collaboration is described as generally unproblematic, with few issues or situations that raised conflicts. The following quote gives an example of the collaboration and what it yields in terms of value.

"Now we realize that here's a mechanism that acts like this and we can describe it like that. Then we present it to each other at work package meetings in the working groups, and there are also these ongoing presentations where everyone who is in the project, the engineers, or the PhD students, present their findings to each other. And of course we do that internally in the company as well, when we are working on something, we review each other's work. But here we get a fresh look at our work from other companies and other universities, and they see something else and ask different questions than the ones we usually ask each other internally. So, the reviews we do of different solutions and findings, they are much more thorough when we work in that type of forum, because we all build on each others' knowledge and challenge each other much more on our professional foundation. So, it becomes much stronger than what we can do as individual parties. I really think that has given me peace of mind, when I say that I am responsible for our technology development, and we face several new technologies that we must decide whether to introduce or not introduce."

As mentioned above, the establishment of testing facilities in the wind energy sector has taken several years to complete in some cases. When projects span across changing governments, it has been important for the wind sector to have the same people in key positions to continually push development. Establishing the equivalent of an industry organization such as Megavind in P2X would likely help maintain focus on development and provide a forum from which decisions that benefit the whole sector can be made and discussed politically. An industry organization is also important for SMEs as they may not have the power/financial power/influence to create change at the political level on their own.

7.0 Summary of findings and perspectives for future technologies

This study has sought to examine what dynamics drive technological development in the wind energy sector eco-system of test and research facilities, focusing on the roles of R&D collaboration and of regulatory and institutional framework conditions.

The challenges and potentials of new green technologies, such as power electronics and P2X, are often compared with those of wind energy 30-40 years ago. At that early stage, wind energy was seen as having potential, but was far from becoming commercially viable in competition with conventional energy sources. Much has changed since those early years. A noteworthy milestone was the onset of zero-subsidy bids, which were first made for offshore wind energy in 2017[19]. The sector now includes large OEMs that are both profitable and able to invest in the development of the sector as a whole, and a complex network of suppliers and sub-suppliers.

Both the historical development of the wind energy sector and the challenges it faces now to maintain a competitive advantage, can be very instructive for new emerging technologies, such as the four areas that have been targeted by the Danish government: carbon capture, climate efficient fuels, climate-friendly agriculture and food production, and re-use and reduction of plastic waste.

In particular, four factors have been identified as being critical ingredients to the Danish wind energy sector's success over the years[20]:

- Political will
- Supportive market and framework conditions
- Support for R&D
- Certification and testing

Arguably, these factors all remain relevant for today's wind energy sector, though in different ways than 30-40 years ago. In the beginning, the main challenge was to establish a new technology, whereas the main challenge now is to keep it at the forefront compared to global competition. They also provide a good background for this study, which seeks both to identify factors for continued development of the wind energy sector and how these results can be transferred to other green technology areas.

In this concluding section, we summarize the main insights from our study, looking both at how they reflect on the wind energy sector and lessons for emerging green technologies. These key findings are related to the role of political support, funding, a collaborative culture and the role of universities and GTS-institutes. While all the findings for the wind energy sector are also relevant for emerging green technologies, there may also be additional perspectives taking into account the context of early technologies that are not yet commercially viable.

Each green technology has its own potentials and challenges and may also differ in terms of infrastructure needs and existing competences in Denmark that can be drawn on. However, there are general lessons from the wind energy sector that should be applicable across many different emerging green technologies.

[19] https://stateofgreen.com/en/uploads/2021/10/Megavind-Annual-Research-and-Innovation-Agenda-2021_web.pdf

[20] The original source of this argument is Henrik Stiesdal. See e.g. https://www.energy-supply.dk/article/view/718789/succesmodel_genanvendt_til_at_redde_danske_arbejdspladser_og_klimaet

The table below summarizes these main points and additional perspectives for emerging green technologies.

The network of state of the art testing and development facilities is seen as a key element within Danish wind energy, covering all main testing needs at a high level. Proximity among testing facilities, R&D departments and universities was also cited as a strength. This system not only supports the development and performance of the Danish wind energy, it also makes it both attractive for firms to keep their R&D operations here or to locate here from abroad.

Political will remains a critical factor in facilitating and supporting the development of the wind energy sector. This involves championing support for sector development, changes in laws and regulations, and securing financing. In many cases, this has also involved a substantial amount of coordination across different ministries and with local governments.

Table 2. Main insights for the wind energy sector and emerging green technologies

Political will
The state plays a central role in implementing changes that are recommended through consensus by the industry. This includes changes to laws, establishing standards and regulations, coordination among public agencies, availability of funding, and security.
Maintaining continuity over time requires consensus across the political spectrum and coordination mechanisms to keep long term plans on track.
New green technologies: Needs are somewhat different for emerging technologies, with greater focus on dispensation and market support, along with a need for a greater coordination role in absence of large industry actors.
R&D funding
The role of R&D funding for collaborations goes beyond financial support; it creates networks, access to facilities. Project funding appears to have a critical role in establishing and growing relationships among actors, and having a shared interest in development work. Through this, public funding can spur additional investment by collaboration partners.
New green technologies: Earlier stage applied research funding is also important, yet less available. This is potentially of even greater importance for emerging technologies. Large grants for new facilities requiring coordination of future needs between market actors and public organisations may provide useful as it did in the wind energy sector.
Collaborative culture
The wind energy sector is driven by a strong shared vision and collective responsibility for strengthening the Danish innovation eco-system. There is a strong awareness of the mutual benefits of collaboration, also among competitors. Trust and long-term relationships are shaped through collaboration. R&D funding projects, university testing facilities and consensus decision making all fuel this collaborative culture. Individual actors in the industry maintaining these relationships over time is crucial due to the amount of time it takes to develop test facilities, which may span across changing governments.
New green technologies: Other technologies should not take this as given. There is a need to examine whether conditions are in place to nurture a collaborative culture. Linking new green technologies to the existing wind energy research and testing eco-system could help to build a collaborative culture.

Support for small and medium enterprises (SME)

Creating and maintaining the right conditions for SMEs is critical for the success of the Danish wind energy sector and for other green technologies. This includes access to funding and testing and research facilities, along with support and exemptions on R&D activities.

New green technologies: Emerging green technologies will likely be much more fragmented than today's wind energy sector, further increasing the importance of efforts to support the development and growth of SMEs.

State of the art testing facilities

A key factor for the innovation eco-system as a whole. Political will is needed, but also conditions for ongoing development of facilities, and interplay between testing and research activities.

New green technologies: This is a dynamic process for new technologies. It cannot be determined too far ahead, but has to follow the needs of the sector.

Universities and GTS-institutes

Universities are not just a source of competences and new research results. They also function as a focal point for collaborative work across different actors in the sector. University-run testing facilities connect to industry through the interplay between testing and development activities. GTS-institutes play a key role in certification activities and establishing standards that are critical for sector development. GTS-institutes also have specific competences that often differ from those at universities.

Several test facilities came to be through one-off large-scale infrastructure or research grants. It is important that these possibilities exist for raising what in some cases is large sums of capital to establish new facilities.

While the state's role has been vital, it has been as a facilitator. Decision making for the sector has not been top-down, but instead have been bottom-up, based on consensus among actors in the sector. The ability to achieve consensus on the direction and framework conditions for the sector has been very important. Megavind and Wind Denmark have played a major role in achieving industry consensus on the strategic planning of large scale investments in facilities – similar organisations would be beneficial in these new areas in order to create a shared vision. There is a risk that open competition and a palisade strategy can lead to cannibalism between new technology areas.

The role of universities in the development of the wind energy sector has evolved over the years, and in some ways has become less central now that the large OEMs have strong and very large R&D capabilities of their own. However, universities still have a role in focusing on more research-based, exploratory work that firms typically do not engage in. In addition, the interviews show the important role of university-run testing facilities as a focal point for many collaborations involving a broad range of actors. In addition, there is a strong degree of interplay between testing and research at university-run facilities.

This suggests that it will be important to support new technologies to both strengthen the conditions for business development activities, and to help ensure that there are strong university research environments that can both contribute to technology development on their own and to bring actors together in collaborative projects.

GTS-institutes continue to play an important role within the testing and certification of wind turbine components and materials, along with the development of testing technologies.

Strong competences within testing are a crucial element for the performance of testing and research facilities and their continued development. While some users are able to conduct testing with their own personnel, it is still vital that facilities have their own knowledgeable and skilled personnel. A number of respondents recommended that even greater focus is placed on educating new engineers with a strong background in testing.

Funding in the wind energy sector from sources such as EUDP, Innovation Fund Denmark and Innovation Fund Europe has had a positive impact on 1) sustainability of partnerships, 2) enabling access to test facilities for many different actors 3) contribution to a high turnover/use on/of test facilities. It is imperative that new green technology fields have access to this type of funding which is relatively easy to apply for, and which can go to development and demonstration projects as well as incentivize interaction between different actors.

While these types of funding have been very successful in supporting R&D and demonstration activities, it was seen as much more difficult to obtain funding for more exploratory, applied work. This was seen as lacking for the wind energy sector, and could be even more important for new green technologies.

Funding mechanisms for large-scale investments in the wind energy sector have been sporadic and often based on one-off facility funding schemes. The rare-event investments in large –scale test- and research facilities require that such funding mechanisms are made available and tailored to the emerging technology field.

Creating and maintaining the right conditions for SMEs is critical for the success of the Danish wind energy sector and for other green technologies. The wind energy sector includes large OEMs, but also an increasingly complex network of SMEs. It is important to ensure that SMEs have access to testing and research facilities, both in terms of cost and testing capacity. Access to funding gives access to knowledge and facilities, and also to broad network of partners. Both network connections and the funded research itself can help SMEs in securing further business and investments from their partners. Regulations and exemptions, which often require local-state coordination, reduce barriers and costs, increasing the viability of SMEs' R&D activities.

Emerging green technologies will likely be much more fragmented than today's wind energy sector, further increasing the importance of efforts to support the development and growth of SMEs.

Wind energy is a global industry with extensive international collaboration across both public and private actors. While this means that Danish companies, universities and GTS-institutes are able to tap into knowledge and facilities abroad, a number of respondents have emphasized that both the completeness of the Danish eco-system of facilities and close proximity to one another is an important strength for the Danish system. This is particularly the case for latter stage testing, where companies need to do frequent testing and where it is a great advantage for facilities to be in close proximity to companies' R&D departments.

As the wind energy sector was able to exploit the shipping and oil industry to develop – there should be an open eye to how existing networks and testing facilities could be used to support new technology areas.

It has taken a long time to build the partnerships and a culture of trust and mutual understanding in the wind energy sector. This cannot be taken for granted in the establishment of new areas. Building new areas from and with actors in the wind energy sector may help transfer the culture to new areas – moreover, making sure that funding instruments are available could help the collaborative culture on its way. It is important however, to remember that new areas of technology will have different competition parameters than the more or less matured wind energy sector.

The long timeframe involved with the development of new green technologies has a number of other implications. One is the continuity of political support. Broad support across the political spectrum, as is the case for the wind energy sector, is needed to ensure that the establishment of new technologies can continue across different sitting governments. It is also important to build up relations and a knowledge base across different government agencies and between state and local government that are able to maintain dialogues and coordinate developments over longer periods of time.

Different government agencies and levels have proved able to coordinate the implementation of new regulations or facilities, though these processes often take several years. Efforts to enhance coordination and reduce the time it takes to implement changes could have substantial benefits for the industry.

References

Granstrand, O., & Holgersson, M. (2020). Innovation eco-systems: A conceptual review and a new definition. *Technovation*, *90*, 102098.

Graversen, E.K. (2017). From tendencies to genuine innovation policy: the Danish case. CFA, Aarhus University. https://pure.au.dk/portal/files/172000820/From_tendencies_to_genuine_innovation_policy_the_Danish_case_Chapter_3_22_07_2016.pdf

Karnøe, P. (1991). Danish wind turbine industry—A surprising international success: On innovations, industrial development and technology policy. *Samfundslitteratur, Copenhagen*.

Karnøe, P., & Garud, R. (2012). Path creation: Co-creation of heterogeneous resources in the emergence of the Danish wind turbine cluster. *European Planning Studies*, *20*(5), 733-752.

Klima-, Energi- og Forsyningsministeriet (2021). Fremtidens grønne brændstoffer. https://kefm.dk/Media/637751860685972853/Fremtidens%20gr%C3%B8nne%20br%C3%A6ndstoffer.pdf

Klima-, Energi- og Forsyningsministeriet (2021). Regeringens strategi for POWER-TO-X. https://kefm.dk/Media/637751860733099677/Regeringens%20strategi%20for%20Power-to-X.pdf

Megavind (2015) Danish Knowledge Institutions and their Contribution to a Competitive Wind energy sector. https://megavind.winddenmark.dk/sites/megavind.winddenmark.dk/files/media/document/danish_knowledge_institutions_and_their_contribution_to_a_competitive_wind_industrypdf.pdf

Megavind (2016). Test and Demonstration Facilities for Wind Energy. https://winddenmark.dk/sites/winddenmark.dk/files/media/document/Megavind%20Test%20Methods%20and%20Facilities%20for%20Wind%20Energy.pdf

Megavind (2020a). Megavind Test Methods and Facilities for Wind Energy. https://winddenmark.dk/sites/winddenmark.dk/files/media/document/Megavind%20Test%20Methods%20and%20Facilities%20for%20Wind%20Energy.pdf

Megavind (2020b). Partnerships in the Danish Wind energy sector Supply Chain. https://winddenmark.dk/sites/winddenmark.dk/files/media/document/Partnerships%20in%20the%20Danish%20Wind%20Industry%20Supply%20Chain.pdf

Uddannelses- og Forskningsministeriet (2020). Fremtidens grønne løsninger Strategi for investeringer i grøn forskning, teknologi og innovation. https://ufm.dk/publikationer/2020/filer/1-fremtidens-gronne-losninger-strategi-for-investeringer-i-gron.pdf

Uddannelses- og Forskningsministeriet (2021). Finansiering af grøn forskning og innovation i 2020. https://ufm.dk/publikationer/2021/filer/kortlaegning-af-finansiering-af-gron-forskning-og-innovation-i-2020.pdf