United Nations Climate Change
Technology Executive Committee

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Wind Energy in Denmark

Case study: Good practices and lessons learned on the setup and implementation of National Systems of Innovation

This document is part of a collection of six case studies selected from the work conducted by the Technology Executive Committee (TEC) on "Good practices and lessons learned on the setup and implementation of National Systems of Innovation". It specifically focuses on the system of innovation of the Denmark's wind energy sector.

The Summary for Policymakers of the TEC's work presented in June 2023[1] explains that the primary objective of an innovation system is to produce, diffuse, and use innovations. To accomplish this objective, the Summary for Policymakers document identifies specific activities or functions that should be carried out to facilitate the innovation process. Based on empirical evidence, innovation studies identify seven main functions as outlined in Table 1. Evaluating to what extent an innovation system can perform these functions is necessary to identify and assess the innovation system's achievements, failures and gaps or barriers.

Table 1. Danish case of innovation system

Country	**Denmark**	**Focus**	**Mitigation**
Scope	**Renewable energy**	**Key innovation system functions (F)[a]**	**F1 Knowledge development and diffusion** **F2 Entrepreneurial experimentation** **F3 Market formation** **F4 Influence on the direction of the search** **F5 Resource mobilization** **F6 Legitimation** **F7 Development of positive externalities**
Approach	**Bottom-up and top-down**	**Starting year**	**1890s to date: local experimentation** **1970s to date: government interventions**

[a] See the Summary for Policymakers of "Good practices and lessons learned on the setup and implementation of National Systems of Innovation",[2] and table 3 for the description of functions.

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[1] TEC (2023). Summary for Policy makers: Good practices and lessons learned on the setup and implementation of National Systems of Innovation, UNFCCC Technology Executive Committee, Bonn. Available at https://unfccc.int/ttclear/tec/NSI.html.

[2] TEC (2023).

1 Introduction to the case

Denmark is considered a frontrunner in wind energy.[3] Among the countries with the highest amounts of wind energy generated per capita,[4] Denmark met 48% of its domestic electricity supply needs in 2020 with wind-generated electricity, the highest share in the world.[5]

Denmark has developed a leading wind energy innovation ecosystem, from innovation to manufacturing and deployment.[6] The Danish technological innovation system (TIS) for wind energy is a network of the world's top manufacturing and export firms, accounting for approximately 2.5% of the country's private sector jobs.[7] The success of the TIS for wind energy is the result of a combination of proactive government policy support and bottom-up initiatives which together have promoted innovation and experience-based learning in the area of wind energy.[8,9] These efforts have allowed the country to build the core competencies required to produce, design and install wind turbines[10] and, more recently, in relation to turbine decommissioning and recycling.[11]

The history of the Danish wind energy industry dates back to 1891, when the first wind turbine was built as a solution for energy access and rural development. Grass-roots experimentation played a major role in innovation in this area, as entrepreneurs and firms in rural Denmark became key actors in promoting early knowledge development via learning-by-doing.[12]

In the 1970s, after the oil crisis, the development of wind energy was systematically integrated into national energy planning as a solution for reducing energy dependency. As environmental concerns increased in the 1990s, wind energy became even more important in Danish central energy planning as the preferred means for driving emission reductions while promoting energy security, local participation and economic development.[13]

This case summarizes the two main channels for the development of the wind energy sector in Denmark: top-down government policy support and bottom-up grass-roots experimentation. This is followed by an assessment of how the combination of these two channels has contributed to the formation of one of the world's leading wind energy innovation systems, while identifying success factors and lessons learned for potential replication.

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[3] IRENA-GWEC (2013). 30 Years of policies for wind energy Lessons from 12 Wind Energy Markets: Denmark. Available at https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2013/GWEC_WindReport_All_web-display.pdf.

[4] Johansen, K. (2021). Wind energy in Denmark: a short history. IEEE power & energy magazine. May/June 2021, pp.94–102. Available at https://vbn.aau.dk/en/publications/wind-energy-in-denmark-a-short-history

[5] IEA Wind TCP (2022). Wind Energy in Denmark. Available at https://iea-wind.org/about-iea-wind-tcp/members/denmark/.

[6] Including materials for wind turbines design and wind-energy-related analysis and services, such as those related to engineering, stakeholder engagement, financing, construction and operation, grid integration and energy storage. See, for example, https://greenpowerdenmark.dk/files/media/winddenmark.dk/document/Profile_of_the_Danish_Wind_Industry.pdf and https://orbit.dtu.dk/en/projects/danish-centre-for-composites-structures-and-materials-for-wind-tu.

[7] Johansen, K. (2021).

[8] Wieczorek et al. (2015). Broadening the national focus in technological innovation system analysis: The case of offshore wind. Environmental Innovation and Societal Transitions 14 (2015), pp.128–148. Available at http://dx.doi.org/10.1016/j.eist.2014.09.001.

[9] Johansen, K. (2021).

[10] Wieczorek et al. (2015).

[11] See, for example, https://www.siemensgamesa.com/newsroom/2021/01/210125-siemens-gamsa-press-release-decomblades-launched and https://stateofgreen.com/en/news/oldies-but-goldies-recycling-wind-turbines-for-new-use/.

[12] Johansen, K. (2021).

[13] IRENA- GWEC (2013).

2 Legislative framework

The legislative framework for the Danish wind innovation system has been developed over the course of the last few decades through the establishment of several national energy plans. These plans have resulted in the establishment of policies, taxes and other incentives, the removal of legislative barriers[14] and the creation of the main national authorities and governing agencies underlying the current TIS.

Denmark is considered a pioneer in the introduction of policies and regulations to incentivize the use and production of wind energy. In line with this role, it introduced an energy tax back in the late 1970s, with the resulting tax revenues allocated to financing research and development related to wind energy. This tax was one of the main funding sources for such research and development at the time. Environmental taxes introduced in the 1980s further supported the development of renewable energy technologies, including wind energy. The country was also one of the first to introduce large subsidies for its nascent wind industry and regulations governing the selling by local energy cooperatives – collectives of wind energy producers from local communities – of their electricity back to the grid. Its feed-in-tariff system designed to support the wind energy by providing a guaranteed, above-market price for producers, was later replicated in other countries.

Moreover, Denmark created a framework for financing the development of wind energy based on a public service obligation (PSO), which imposed taxes on energy consumers, which were used to finance subsidies and grants for wind energy.[15] Later on, the PSO was phased out gradually between 2017-2021 by the Danish Government.

The Danish Ministry of Energy (MoE) was first established in the late 1970s and is responsible for, inter alia, energy planning and coordinating the country's energy-related research and development efforts.[16] The Danish Energy Agency (DEA), an agency under the MoE, is responsible for tasks regarding energy production, supply and consumption. It is the regulatory authority for the electricity grid and establishes the associated supply obligations. It is also responsible for coordinating the Danish energy transition on behalf of the Government and national greenhouse gas (GHG) emission reduction efforts.[17] The DEA also offers expertise in this area to other countries in association with other technical institutions in Denmark.[18]

In addition to the above, international agreements, such as the Kyoto Protocol and the Paris Agreement, have influenced the formulation of national targets for renewable energy by helping to put environmental goals higher on the national agenda and mobilize public support for renewable energy.[19]

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[14] Such as allowing independent power producers to deliver power to the grid.

[15] IRENA-GWEC (2013), Wieczorek et al. (2015) and Johansen, K. (2021).

[16] It has been renamed to the Ministry of Climate, Energy and Utilities, in November 2007

[17] Energy-related as well as non-energy-related emissions. See https://ens.dk/en/about-us/about-danish-energy-agency and https://iea-wind.org/

[18] See https://um.dk/en/-/media/websites/umen/danida/results/evaluation-of-development-assistance/evaluation-programmes/2021mitigationannexs.ashx.

[19] Johansen, K. (2021).

3 The Danish national system of innovation

Denmark has a highly developed national innovation system. Danish knowledge institutes top international rankings in terms of number of publications on wind energy,[20] with such institutes as the Risø National Laboratory for Sustainable Energy,[21] as well as Aalborg University and Technical University of Denmark (DTU), considered to lead the field globally. These three institutes offer polytechnic (vocational) training in the field of wind energy and are frontrunners in terms of number of master and PhD graduates specializing in various aspects of wind energy.[22]

Stakeholders in National networks of innovation are also well interconnected. There is strong collaboration between universities, industry and technology users.[23] The DTU has a Centre for Technology Entrepreneurship, which teams up students and researchers with entrepreneurs with the purpose of realizing wind-energy-related start-ups. For example, Aalborg University is collaborating with electric utility Dong Energy; wind turbine manufacturer Vestas is sponsoring PhD students at Aalborg University;[24] and wind turbine manufacturers like Vestas, Siemens and LM have offices at DTU and in Aalborg.[25] Denmark's networks for innovation collaboration also extend to the international sphere. For instance, Denmark is an active member of the International Energy Agency Wind Technology Collaboration Programme.[26]

The two largest public funding programmes in Denmark are the Energy Technology Development and Demonstration Programme, administered by the DEA, and the Innovation Fund Denmark. Moreover, wind energy is supported via 'green labs' that offer large-scale testing facilities for climate technology demonstration.[27] In addition to public funding for research and development arising from energy and environmental taxes, many pension funds in Denmark invest in wind energy owing to the widespread perception of wind being a safe investment. While renewable energy is often perceived as unknown and risky by the financial sector, this is different in Denmark as a result of the decades-long history of wind energy in the country.

Local circumstances, such as the Danish climate and a lack of fossil fuel resources, have also been important incentives for the development of wind energy in Denmark. Denmark has a long coastline with consistently strong winds, and there are no other natural (commercial) energy resources such as coal or gas or the geographical conditions for hydropower.[28] These conditions prompted Danish scientists and engineers to develop and experiment with wind technology at an early stage.

Table 2 summarizes the main historical events that have shaped the Danish wind innovation system.

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[20] Wieczorek et al. (2015).

[21] Risø National Laboratory for Sustainable Energy was a scientific research organization, founded in 1956, that became an institute of the Technical University of Denmark (DTU) in 2008. It was dissolved in 2012, now it is known as the DTU Risø Campus, home to a number of institutes under the DTU, including UNEP Copenhagen Climate Centre.

[22] Wieczorek et al. (2015).

[23] Wieczorek et al. (2015) and Kamp (2008). Socio-technical analysis of the introduction of wind power in the Netherlands and Denmark. International Journal of Environmental Technology and Management (9), p.184.

[24] The Vestas Power Programme (2008–2013), for instance, sponsored 10 PhD students in three main topics: power electronics, power systems and electrical energy storage. It aimed to identify the most suitable converter technology and control strategy for large turbines in large wind farms; assess the impact of the large expansion of wind power on utility stability and reliability; and determine the most suitable storage technology for enabling higher wind energy grid integration. See https://vbn.aau.dk/en/projects/vestas-power-programme.

[25] Wieczorek et al. (2015).

[26] The Programme consists of 23 countries and sponsor members that share information and collaborate on research activities to advance wind energy deployment. See International Energy Agency Wind Technology Collaboration Programme (2022). Wind Energy in Denmark. Available at https://iea-wind.org/about-iea-wind-tcp/members/denmark/.

[27] International Energy Agency Wind Technology Collaboration Programme (2022).

[28] Vestergaard, J., Brandstrup, L., Goddard, R. (2004). A Brief History of the Wind Turbine Industries in Denmark and the United States. Academy of International Business (Southeast USA Chapter) Conference Proceedings, November 2004, pp.322–327.

Table 2. A timeline of wind energy in Denmark[29]

Year	Key Events and Political Decisions
1891	Wind turbine by Poul la Cour
1903	Danish Wind Electricity Company (D.V.E.s.) founded
1914	1914-1918: World War I
1919	Wind turbine with aerodynamic wings; design J.Jensen and P. Vinding
1939	1939-1945: World War II
1950	The Vester Egesborg turbine
1952	Application for Marshall Plan support for wind power research
1963	Silent Spring, book by Rachel Carson
1973	90% of the total national energy consumption based on imported oil
1973	First international energy crisis
1976	Danish Energy Policy 1979
1978	The Tvind turbine, the largest in the world at the time
1979	Second international energy crisis
1979	Public protests against nuclear power
1979	Danish Energy Policy 1979
1985	Parliamentary decision: “no” to nuclear
1987	The Brundtland Report
1990	Energy 2000, the first plan for low-carbon energy transitions in the world
1991	Vindeby Offshore Wind Farm, the first offshore wind farm in the world
1992	United Nations Framework Convention on Climate Change
1997	The Kyoto Protocol implements objectives of the United Nations Framework Convention on Climate Change
2000	13% of the total national electricity consumption supplied by wind power
2004	Energy Agreement
2006	An Inconvenient Truth, book by Al Gore
2008	2008-2011: Energy Agreement and Renewable Energy Act
2010	Anholt Offshore Wind Farm; the largest in the world at the time
2012	2012-2018: Energy Agreement
2015	Paris Agreement signed by 197 countries
2018	46.9% of the total national electricity consumption supplied by wind power
2018	Energy Agreement
2019	Climate Act

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[29] Source: Johansen, K. (2021).

4 Description of the case

The successful development of the wind energy innovation system in Denmark is the result of two complementary processes: proactive, consistent and systematic government planning and interventions (top-down) and bottom-up experimentation via local entrepreneurs and cooperatives. These processes are explained in the relevant sections below, though it is important to note that the successful development of the wind energy innovation system was due to the interaction and complementarity between these processes.

4.1 Bottom-up community initiatives in rural areas

In rural areas in Denmark, wind energy developed as a way to promote rural development. In 1881, Poul la Cour, a local meteorologist, natural sciences professor and inventor, constructed the first wind turbine for producing electricity. His background in meteorology attuned him to the possibilities of using wind for electricity generation rather than pumping water or milling grain, a concept rejected in other countries at the time owing to low efficiency of the wind energy generation technology. It also led to future work on wind tunnels and aerodynamics for windmill design.[30]

La Cour aimed to provide rural populations with a means of energy access that would allow for the mechanization and modernization of farming practices, as well as provide heat and light.[31] La Cour taught courses for 'wind electricians' at the local 'folk high school'[32] and, in 1903, established the Danish Wind Electricity Company (D.V.E.S.) together with some of his students and other partners. D.V.E.S provided training to electricians in rural areas on how to build and operate small wind energy plants. By 1918, 120 wind-powered electricity generation plants were already delivering 3% of Denmark's total national electricity. About 25,000 private farms deployed small private wind turbines for powering machinery.[33]

By the 1930s, wind energy plants had become common in the Danish countryside. There was much experimentation with emerging wind energy technologies by grass-roots entrepreneurs. The Danish Wind Energy Association was created in 1919 and received financial support from the Government. During this time, the development of the Danish wind energy industry was driven in particular by companies such as Lykkegaard Ltd.[34] and cement manufacturer FLSmidth, in cooperation with aircraft manufacturer Kramme & Zeuthen.[35] However, during the inter-war period, decentralized wind energy lost terrain to centralized coal-fired power stations owing to the expansion of the national grid. It did, though, help to alleviate the effects of power outages during World War II.[36,37]

After World War II, another of la Cour's former students initiated a research and development programme on wind energy. Their efforts, bolstered by funding from the Danish association for power stations, led to the realization of the Gedser machine in 1959, which formed the basis for the modern wind turbine. By 1978, around 10 companies for small wind turbines had been established thanks to the knowledge generated from experience with the Gedser machine. These companies additionally drew on existing knowledge of agricultural machine manufacturing to learn how to make wind turbines, often by trial-and-error,[38] and gained access to knowledge of earlier wind turbines during 'Wind Meetings', where knowledge and experience were shared between wind turbine manufacturers, owners and researchers.[39]

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[30] See, for example, Gipe, P., Möllerström, E. An overview of the history of wind turbine development: Part I—The early wind turbines until the 1960s. Wind Engineering. 2022;46(6):1973–2004. doi:10.1177/0309524X221117825; and Warnes, K. Windows into History: Poul la Cour pioneered wind power in Denmark, available at https://windowstoworldhistory.weebly.com/poul-la-cour-pioneered-wind-power-in-denmark.html.

[31] Johansen, K. (2021).

[32] Folk high schools (in Danish: Folkehøjskole) are institutions for adult education that generally do not grant academic degrees. See https://danishfolkhighschools.com/about-folk-high-schools/what-is-a-folk-high-school.

[33] Johansen, K. (2021).

[34] Founded by one of la Cour's former students.

[35] Vestergaard et al. (2004).

[36] Johansen, K. (2021).

[37] Vestergaard et al. (2004).

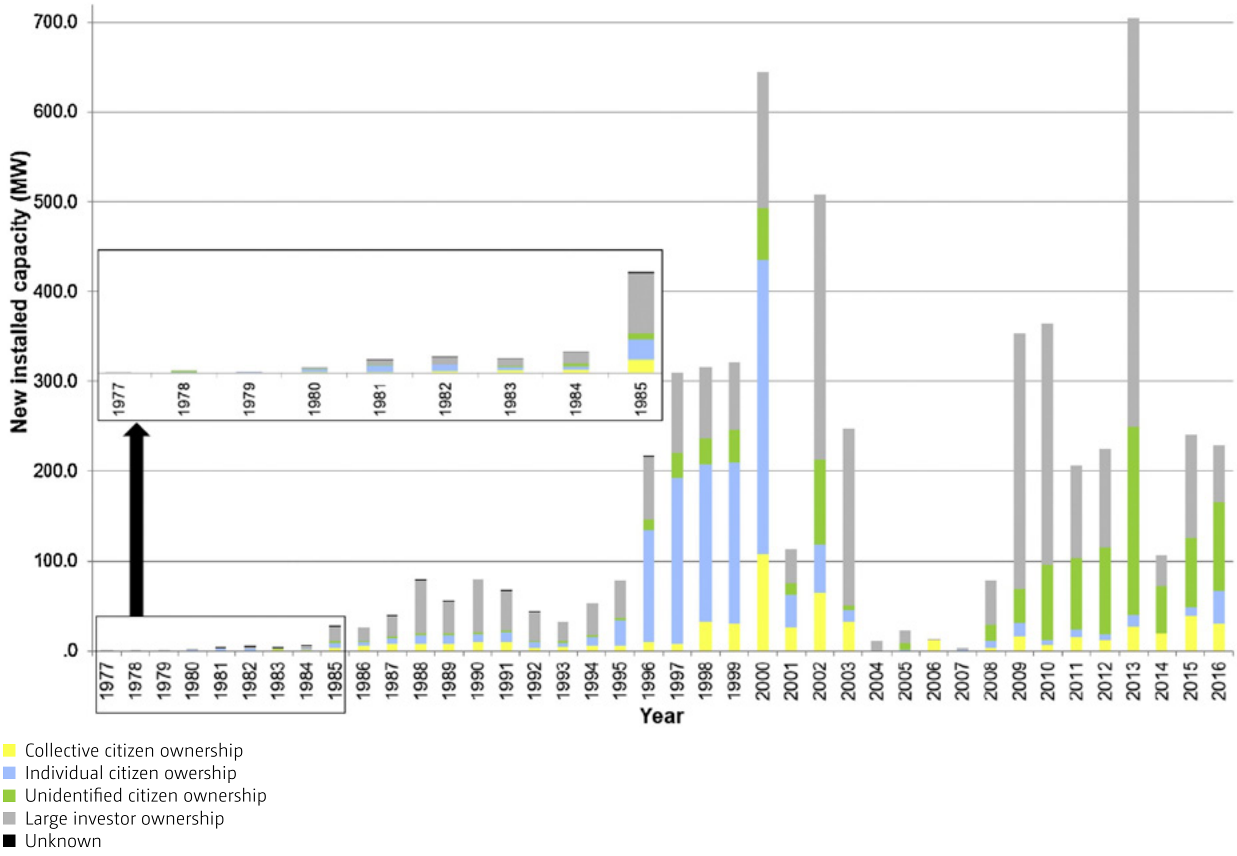
[38] Kamp (2008).

[39] Kamp (2008).

However, the electricity generation costs for the Gedser machine were twice those for producing oil- or coal-based electricity.[40] As a result, the Danish association for power stations came to see wind energy as uncompetitive.[41] Those concerns led to a halt in wind energy research until the 1970s, when the first energy plan resumed funding for wind energy research and development and created incentives leading to the formation of wind energy cooperatives (see also the next section 4.2).

In the 1980s, environmental awareness and anti-nuclear sentiment were growing in Denmark. Rene¬wable energy sources, including wind and solar, became widely supported by local communities as locally available green and sustainable resources.[42] This, together with the support from the national energy plans, resulted in a more favourable environment for wind energy. By the late 1990s, there were over 2,100 wind energy cooperatives, including more than 100,000 families owning almost 90% of the 6,300 wind turbines in operation in the country.[43] This strong community ownership and the resulting benefits fostered substantial public support for wind energy and supporting policies in the country.[44]

Figure 1. Installation of wind capacity in Denmark by type of owner[45]



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[40] Johansen, K. (2021).

[41] Vestergaard et al. (2004).

[42] Johansen, K. (2021).

[43] IRENA-GWEC (2013) and Johansen, K. (2021).

[44] IRENA-GWEC (2013).

[45] Source: L. Gorroño-Albizu, K. Sperling, S. Djørup, 2019, The past, present and uncertain future of community energy in Denmark: Critically reviewing and conceptualising citizen ownership, Energy Research & Social Science, Volume 57, 2019, 101231, ISSN 2214-6296, available at https://doi.org/10.1016/j.erss.2019.101231.

4.2 Government initiatives: energy plans

Government actions supported the bottom-up developments described in the previous section, for instance by providing financial support to the Danish association for wind energy and creating incentives for the formation of local wind energy cooperatives.

Since the 1970s, the Danish Government has contributed to the development of a wind energy TIS through the national energy plans. The first energy plan (of 1976) aimed to create energy security in the context of the first oil crisis. Wind energy was seen as a solution for reducing energy dependency and as an alternative to nuclear energy, which faced public opposition in Denmark at the time. Reports from independent energy experts helped to put wind energy forward as a key alternative.

The most relevant outcomes during this period were the creation of an energy tax and the establishment of the MoE.[46] The creation of the energy tax provided financial support for public research, spreading the costs among all electricity customers. The DTU was the key actor to receive funding for research while the MoE was in charge of coordination of the national wind energy system. The MoE envisioned a wind energy system based on large-scale wind parks built by consortia of large Danish firms and owned and operated by utilities. As a result, government-funded research at this time focused on the development of large-scale wind turbines.[47]

A multi-stakeholder collaborative approach was strongly present during this period. For example, in the late 1970s, companies were reluctant to build Nibe turbines owing to the perceived risks. Risø, the DTU and the SEAS utility got involved to partially finance the wind turbines. When the wind energy department was created at Risø, funding constraints encouraged collaboration with wind turbine manufacturers to secure additional sources of funding. This facilitated the exchange of knowledge and made learning-by-interacting very effective.[48]

Policies in the 1980s consolidated the foundations of the domestic wind industry, helping to create a market for wind turbines and renewable electricity. The second energy plan (of 1981) created tax incentives for cooperatives and introduced an option that allowed them to sell excess electricity to the grid. In addition, it established the first subsidies for the construction and operation of wind parks. This led to an explosion in the number of cooperatives and installation of wind energy capacity, helping the Danish wind industry to increase in scale.[49]

In addition to domestic trends, subsidies introduced for wind energy in California resulted in increased Danish exports of wind turbines to that region. This increase was driven by publications by the Danish Windmill Owners Association on the performance of several types of turbines, which helped to create a good reputation for Danish wind energy technology.[50] After sales to the Californian market decreased in 1985, the Danish Government drew up the 100 MW agreement, which aimed to increase the scope of the domestic wind energy market by setting clear targets for additional wind energy capacity in the upcoming decades.[51] In 1988, subsidies were reduced, given that the domestic market had been successfully expanded by that time and technology developments were deemed to have made wind energy naturally attractive. Research and development subsidies and grants for replacing aging turbines remained in place, however. Moreover, the Government started to establish legal requirements for utilities to purchase electricity generated by wind energy producers.

Wind energy gained even more in importance in the early 1990s, when the third national energy plan introduced specific targets for wind energy, which was required to account for 10% of national electricity generation to help achieve emission reduction goals agreed under the Kyoto Protocol. To achieve the wind energy target, the plan set the price for wind-based electricity at 85% of the retail electricity rates to make wind energy more attractive, and guaranteed interconnection to the grid for wind parks. In addition, the plan established public planning procedures to explore any latent wind energy potential. These procedures involved public hearings, which helped to coordinate priorities and actions among actors and promoted public acceptance of wind energy. A fixed feed-in-tariff was later introduced, decoupling the wind electricity price from retail prices, and refunds on the energy tax and the carbon tax were provided. This substantially increased revenues for wind power producers.[52]

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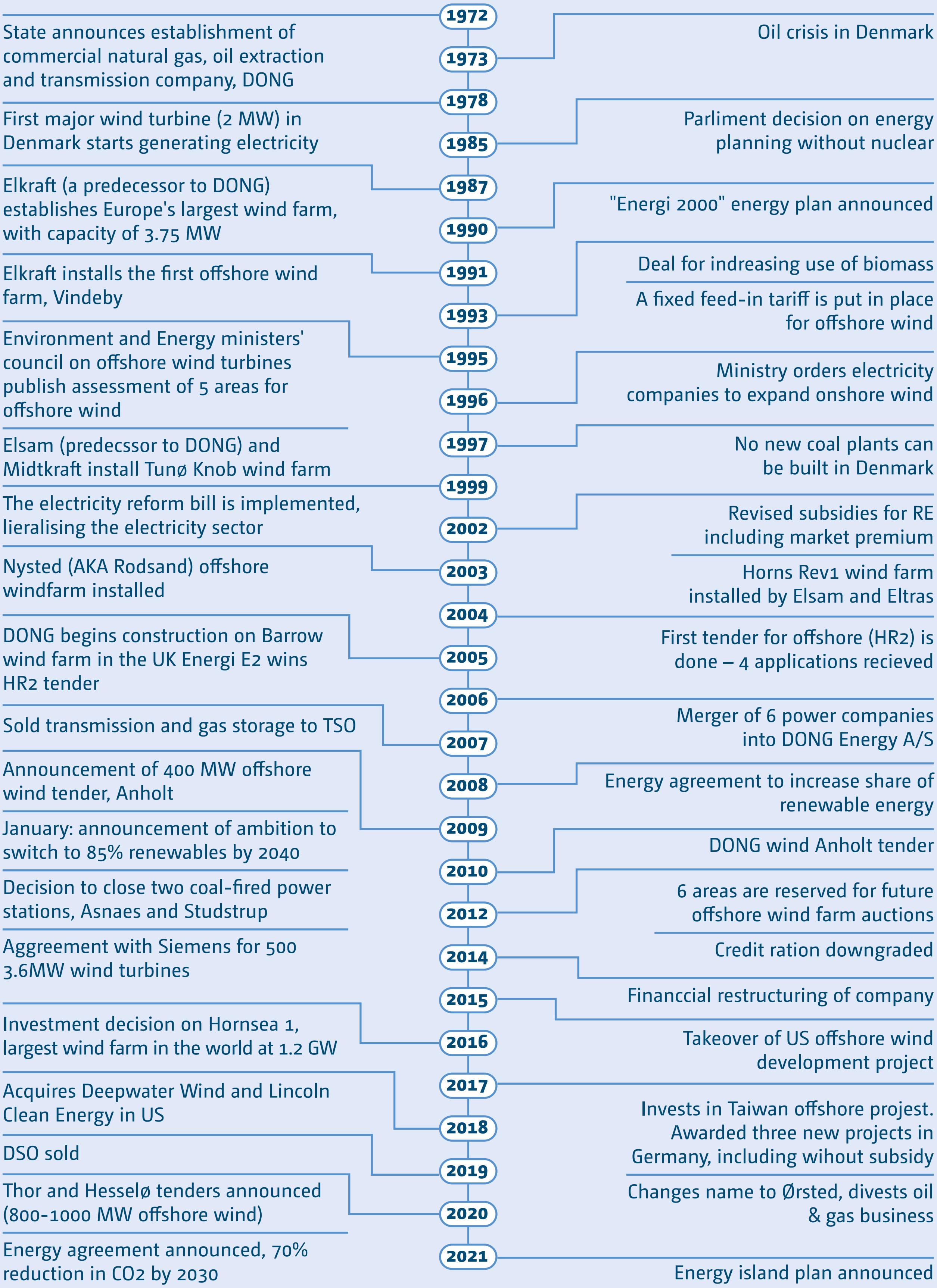
[46] IRENA-GWEC (2013).
[47] Kamp (2008).
[48] Kamp (2008).
[49] IRENA-GWEC (2013).
[50] Kamp (2008).
[51] These targets were then updated – and increased – in 1990 and 2000. See IRENA-GWEC (2013).
[52] IRENA-GWEC (2013).

Figure 2. Key milestones in Denmark's transition to green energy – 1972–2021[53]



State announces establishment of commercial natural gas, oil extraction and transmission company, DONG	1972	
	1973	Oil crisis in Denmark
First major wind turbine (2 MW) in Denmark starts generating electricity	1978	
	1985	Parliment decision on energy planning without nuclear
Elkraft (a predecessor to DONG) establishes Europe's largest wind farm, with capacity of 3.75 MW	1987	
	1990	"Energi 2000" energy plan announced
Elkraft installs the first offshore wind farm, Vindeby	1991	
	1993	Deal for indreasing use of biomass A fixed feed-in tariff is put in place for offshore wind
Environment and Energy ministers' council on offshore wind turbines publish assessment of 5 areas for offshore wind Elsam (predecssor to DONG) and Midtkraft install Tunø Knob wind farm	1995	
	1996	Ministry orders electricity companies to expand onshore wind
	1997	No new coal plants can be built in Denmark
The electricity reform bill is implemented, lieralising the electricity sector	1999	
	2002	Revised subsidies for RE including market premium Horns Rev1 wind farm installed by Elsam and Eltras
Nysted (AKA Rodsand) offshore windfarm installed	2003	
	2004	First tender for offshore (HR2) is done – 4 applications recieved
DONG begins construction on Barrow wind farm in the UK Energi E2 wins HR2 tender	2005	
	2006	Merger of 6 power companies into DONG Energy A/S
Sold transmission and gas storage to TSO	2007	
	2008	Energy agreement to increase share of renewable energy
Announcement of 400 MW offshore wind tender, Anholt January: announcement of ambition to switch to 85% renewables by 2040 Decision to close two coal-fired power stations, Asnaes and Studstrup Aggreement with Siemens for 500 3.6MW wind turbines	2009	
	2010	DONG wind Anholt tender
	2012	6 areas are reserved for future offshore wind farm auctions Credit ration downgraded
	2014	Financcial restructuring of company
	2015	Takeover of US offshore wind development project
Investment decision on Hornsea 1, largest wind farm in the world at 1.2 GW	2016	
	2017	Invests in Taiwan offshore projest. Awarded three new projects in Germany, including wihout subsidy Changes name to Ørsted, divests oil & gas business
Acquires Deepwater Wind and Lincoln Clean Energy in US	2018	
DSO sold	2019	
Thor and Hesselø tenders announced (800-1000 MW offshore wind) Energy agreement announced, 70% reduction in CO2 by 2030	2020	
	2021	Energy island plan announced

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[53] Source: State of Green, 2021. From black to green – a Danish sustainable energy growth story A case study of how an energy utility can transition from fossil fuels to renewable energy and the enabling regulatory framework that made it possible, available at https://ens.dk/sites/ens.dk/files/Globalcooperation/sog_fromblacktogreenreport_210x297_v08_web_spreads.pdf


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As part of the efforts to harmonize and liberalize the internal energy market of the European Union (EU), Denmark went through a liberalization period in the 1990s, which led to major reforms in its energy sector. As part of these reforms, the feed-in-tariff was halted and the guaranteed interconnection to the grid removed. These measures were replaced by the Renewable Portfolio Standard (RPS). Despite the RPS, the following period saw a stagnation in the Danish wind energy sector.[54] This was caused by the political views at the time, requiring renewable energy to be able to compete in the market. As a result, the renewable energy premium under the RPS was capped, and interconnection was no longer ensured.[55]

In the mid-2000s, some measures helped to overcome this stagnation. Megavind, a public–private partnership for supporting the development of wind power in Denmark, was established in 2006 as part of a plan to promote eco-efficient technologies.[56] In addition, the Government approved plans for two offshore wind parks and increased targets for renewable energy. It also created an environmental premium to be added to the electricity market price and introduced compensation for grid-balancing costs.[57] Research, development and deployment funding for energy technology was increased, and renewable electricity tariffs started to be established via special tenders managed by the DEA. In addition, the Government created a PSO to help finance grid connections.[58]

A new energy plan (the Energy Agreement), introduced in 2012, established an ambitious target for wind energy to account for 50% of national electricity generation by 2020 as well as to install 3,300 MW in new wind energy capacity, financed by the PSO. In 2018, the updated Energy Agreement established a target for 55% of the country's energy needs to be met by renewable energy by 2030, mainly through wind and solar energy.[59] Moreover, in the Climate Agreement from 2020 it was decided to initiate the development of two energy islands (located in the North Sea and the Baltic Sea) to utilize offshore wind resources.[60]

This systematic establishment and revision of clear and ambitious national targets, together with financial and regulatory incentives, successfully bolstered the Danish wind energy sector after the stagnation period.[61]

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[54] Legislation to adopt the associated green certificate trading scheme was not adopted. IRENA-GWEC (2013).
[55] IRENA-GWEC (2013).
[56] Wieczorek et al. (2015).
[57] Paid by the grid operator to electricity producers, suppliers or (large) consumers for adjusting their supply or demand to help balance the electricity grid.
[58] IRENA-GWEC (2013).
[59] IRENA-GWEC (2013).
[60] International Energy Agency Wind Technology Collaboration Programme (2022).
[61] IRENA-GWEC (2013).

5. Assessment of the case functions

Bottom-up experimentation contributed to knowledge development and positive externalities in the first half of the 20th century. However, developments stagnated owing to the lack of competitiveness of wind energy in the liberalized, centralized, coal-dominated electricity market.

Top-down interventions from the Government helped overcome this by establishing favourable regulations, creating a better market for renewable energy, increasing the legitimacy of wind energy in national energy planning, providing coordination and a national direction, and mobilizing funding and subsidies for research, development and deployment in relation to wind energy technologies.

The interaction between top-down interventions and bottom-up initiatives has led to the establishment of a wind TIS where local cooperatives have high degrees of ownership and wind energy is aligned with local societal goals of energy access and sustainable energy, which in turn has secured widespread public support for the development of wind energy in Denmark.

The following points discuss the vital systemic functions performed by the wind energy sector in Denmark, which have strengthened the Danish innovation system's structural elements. The table 3 is taken from the Summary for Policymakers of "Good practices and lessons learned on the setup and implementation of National Systems of Innovation" and describes the systemic functions.[62]

Table 3 Functions of systems of innovation[a]

Number	Function	Description
F1	Knowledge development and diffusion	Expansion and intensification of the knowledge base of the innovation system, dissemination of knowledge among actors in the system, creation of new combinations of knowledge
F2	Entrepreneurial experimentation	Designing business models for emergent technologies and knowledge, practices of uncertainty reduction through experimentation with new technologies, applications and strategies
F3	Market formation	Creation of a space or an arena in which goods and services can be exchanged between suppliers and buyers. Includes processes related to definition of demand and choices, positioning (pricing, segmentation) of products, regulation of standards and the rules of exchange
F4	Influence on the direction of search	Processes that influence the direction of research of firms and other actors; that is, which technologies they explore, which problems or solutions they choose to invest in, where they channelize their resources from, etc.
F5	Resource mobilization	Processes by which the system acquires the resources required for innovation, which could be financial and human resources (workforce and capabilities), complementary assets such as infrastructure, etc.
F6	Legitimation	Mechanisms by which an emergent technology, its developers and the TIS in question attain regulative, normative and cognitive legitimacy as viewed by the stakeholders concerned
F7	Development of positive externalities	Creation of system-level utilities (or resources), such as pooled labour markets, complementary technologies and specialized suppliers, which are also available to system actors that did not contribute to building them up

[a] Adapted from Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., & Rickne, A. (2008). Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. Research policy, 37(3), 407-429.

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[62] TEC (2023).

Knowledge development and diffusion

Both bottom-up and top-down initiatives have contributed to knowledge development. At the beginning, the work of individual innovators was crucial to developing knowledge relating to wind turbines. La Cour in particular played a key role in knowledge diffusion, both at the 'folk high school' (where many of his former students followed in his footsteps to work in the wind sector) and through the training provided by his company in rural areas of Denmark. Research and development funding from the Government and private companies is used for wind research in Danish universities, which are also a key mechanism of knowledge diffusion via wind-focused educational programmes. Specialist publications, the 'Wind Meetings', the organization of public hearings and the collaboration networks between companies and universities have been and are still key contributors to knowledge diffusion among knowledge developers and users.

Entrepreneurial experimentation

Entrepreneurial experimentation has been undertaken mainly by local cooperatives and grass-roots entrepreneurs, initially driven by concerns related to economic development and energy access in rural communities. The Gedser machine was a milestone for creating knowledge and experimenting with the three-blade horizontal-axis wind turbine design that would later become the dominant wind energy technology. Later, multi-stakeholder partnerships were crucial to further experimentation with wind technologies, for instance the case of the Nibe turbines and university–industry collaboration, as well as public–private partnerships like Megavind (see section 4.2).

Market formation

Despite the initial success of the bottom-up development of wind energy technologies in the early 20th century, wind-based electricity was very much seen as uncompetitive at the time, which became a barrier to the further development and uptake of wind energy technologies. Later on, government policies and regulations played a major role in creating incentives for developing a domestic market for wind energy.[63] The development of international markets also played a key role in the development of the wind industry in Denmark, first via subsidies in the Californian market that resulted in increased Danish exports of wind turbines to that region, and later with the introduction of targets for wind energy in many countries around the world to help them meet their GHG targets. The growing international market allowed the Danish industry to keep growing, with close to 100% of the wind turbines manufactured in Denmark being exported between 2004 and 2013.[64]

Influence on the direction of the search

Target-setting under the national energy plans helped shape expectations that wind energy would become a major source of electricity generation in the country. This helped to reduce uncertainty about the future viability of wind energy. The coordination of research and development programmes by the MoE helped to shift the focus onto the development of large-scale wind turbines and the concept of a system consisting of large-scale utility producers. This was, however, different from the vision of local communities, which envisaged a system based on cooperative ownership. The end result was a combination of these two visions, in part thanks to public planning procedures that promoted the engagement of both government and local stakeholders when planning the development of the wind energy system. La Cour's wind turbine and the Gedser machine were important developments that helped to provide an initial direction for future technological change that further policies could build upon. Specialist publications shared information on technical progress and contributed to shaping expectations y highlighting recent developments and providing statistics and information about available technologies.

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[63] For instance by implementing regulations that required utilities to purchase electricity from wind energy producers, establishing competitive prices, and providing subsidies and tax exemptions, as well as guarantees for grid connection.

[64] IRENA-GWEC (2013).

Resource mobilization

The introduction of energy and environmental taxes contributed to the mobilization of resources for energy-related research and development, including wind energy. Consumers also contributed to promoting wind energy via the PSO, which helped to finance, inter alia, grid connections for wind parks. Private companies had already been funding deployment and experimentation activities from an early stage. Currently, private companies they are an important source of funding for research at universities via industry–university collaboration. This multi-stakeholder collaboration was a key success factor for reducing investment risks and driving the construction of Nibe turbines forward. This innovation system function also impacts other functions. Tax incentives for cooperatives helped them increase their revenues and hence created positive externalities. Budget constraints required universities to look for funding from industry and thus helped to establish knowledge-sharing networks, which now support the well-functioning knowledge-sharing and learning-by-interacting functions in the Danish TIS

Legitimation

The Government has contributed to the legitimation of wind energy in Denmark by including clear targets for the technology in its long-term planning and systematically revising them to increase ambition levels when needed. Studies from independent experts helped to make wind energy an attractive alternative to nuclear energy in the 1970s. The oil crisis highlighted the downsides of international energy dependency, which increased the legitimacy of other energy technologies, while specialist publications helped to show that Danish wind energy technologies could offer a cost-effective solution for electricity production. Meanwhile, the increase in environmental concerns regarding both climate change and nuclear energy led countries to include wind energy in their national planning to help achieve environmental and energy security goals. A participatory approach to energy planning, together with the local benefits of community ownership, helped increase public acceptance of wind energy, resulting in relatively low resistance to wind energy compared with other countries. The fact that the sector has been responsible for substantial job creation has also helped to legitimate the technology.

Development of positive externalities

The successful development of the wind energy sector in Denmark can in large part be explained by the development of positive externalities. From the beginning, benefits such as rural development, energy access and the availability of a back-up for the national electricity grid for reducing oil dependency were the main drivers for the development of the first wind turbines and the establishment of national manufacturers. The possibility of increasing energy security with an environmentally friendly and safe resource was the main driver for support for wind energy after the 1970s. Today, the fact that the wind industry is a major export industry employing a large number of people is behind much of the public support for wind energy technologies in Denmark. Since local cooperatives own a large part of the wind-based electricity production capacity, this provides an additional source of revenues for communities in the countryside, which has also strongly increased public support, facilitating more ambitious policymaking.

Table 4 summarizes the structure-function coupled analysis of the Denmark’s wind energy sector.

Table 4. Structure-function coupled analysis of the Danish wind energy sector

Function[a]		Structural element	Interventions in the Danish wind energy innovation system
F1	Knowledge development and diffusion	Actors	• Knowledge development and diffusion via individual scientists in rural areas (e.g. in the Askov Folk High School and via the D.V.E.S) helped to increase the capabilities of local communities with regard to wind energy production, which later resulted in a TIS with strong community ownership • The Government established wind-energy-related research and development funding lines, promoting knowledge development at universities • Experimentation by small companies contributed to knowledge development regarding small-scale wind turbines • The creation of master's degrees and PhD and technical education programmes at universities is boosting the wind energy capabilities of the innovation system actors
		Institutions[b]	• The planning procedure/public hearings allowed for more prompt knowledge diffusion between government actors at different levels and local communities
		Interactions	• The 'Wind Meetings' and specialist publications formed a strong network for knowledge diffusion • University–industry interactions contribute to knowledge development between knowledge producers and users and help to diffuse knowledge among actors
		Infrastructure	• The creation of university research centres on wind energy helped to develop/diffuse knowledge in academic institutions and via industry collaboration
F2	Entrepreneurial experimentation	Actors	• Individual scientists played a key role in promoting early bottom-up experimentation • Companies from rural areas wishing to become turbine manufacturers promoted experimentation in manufacturing, allowing them to learn on the go
		Institutions[b]	• Experimentation came first to provide energy access or a back-up to centralized power generation • Early experimentation in rural areas contributed to the formation of a wind TIS with strong community ownership
		Interactions	• D.V.E.S was formed to promote experimentation with wind technologies in rural areas. The creation of associations/cooperatives also strengthened networks • Financing for some demonstration projects by multi-stakeholder partnerships strengthened interactions between actors, promoting experimentation
		Infrastructure	• The first wind turbines in Denmark resulted from entrepreneurial experimentation. The Gedser machine in particular was a milestone for modern wind turbine design
F3	Market formation	Actors	• The Government played a major role in creating the conditions that enabled wind energy to become competitive and have a market. This enabled cooperatives to further expand their wind energy production, which then helped to boost the local wind turbine manufacturing industry
		Institutions[b]	• The creation of policies and incentives, especially energy taxes, subsidies, environmental premiums and guaranteed grid connections, were crucial for creating a market for wind energy, which was seen as uncompetitive at the beginning
		Interactions	• Interactions at the international level also contributed to demand for the wind energy industry in Denmark, first via subsidies in California, and later as a result of other countries' increasing ambition to deploy wind energy technologies to help them reach their mitigation targets
		Infrastructure	• Subsidies substantially increased the deployment of wind parks, which now account for half of Danish electricity generation

[a] See the Table 3 for the description of functions

[b] References to institutions as a structural element in this table are to systems of formal and informal rules.

Table 4. (continued) Structure-function coupled analysis of the Danish wind energy sector

Function[a]		Structural element	Interventions in the Danish wind energy innovation system
F4	Influence on direction of search	Actors	• The MoE, which coordinates government-funded research and development, played a key role in determining the direction of knowledge development at universities, especially for large-scale wind turbine systems • Local cooperatives and scientists, together with smaller manufacturers, contributed to the vision of wind energy as a solution for local socioeconomic development, entailing a more community-owned system with smaller-scale turbines • Independent experts and local communities that opposed nuclear energy helped to make wind energy an alternative for reaching Danish energy goals
		Institutions[b]	• National energy plans set long-term targets for wind energy, helping to shape expectations that the technology would become a key solution for energy security, environmental sustainability and economic development • International agreements highlighted the role that wind energy could play in future energy systems • Specialist publications helped to set standards and best practices and shape expectations concerning the future development of wind energy technologies
		Interactions	• Interactions during the 'Wind Meetings' facilitated the sharing of knowledge and guiding of expectations concerning wind energy production • Public hearings included in planning procedures strengthened coordination between the Government and local actors, making wind energy planning more participatory and including different stakeholder perspectives
		Infrastructure	• The first turbines developed through experimentation in rural Denmark played a key role in setting the direction for the further development of wind turbines and the origin of design standards and procedures (e.g. the currently dominant three-blade horizontal-axis design)
F5	Resource mobilization	Actors	• Multiple actors contributed to mobilizing resources, including local cooperatives, individuals, companies, universities and the Government • Consumers also played a key role in mobilizing resources in the Danish wind TIS following the establishment of energy taxes and PSOs
		Institutions[b]	• The establishment of energy and environmental taxes was a major contributor to mobilizing funding for research and development related to wind energy in Denmark • The creation of a PSO contributed to the financing of grid connection costs for wind parks • The introduction of feed-in-tariffs, and subsidies for building/operating wind parks and replacing aging turbines helped to mobilize resources for wind energy producers
		Interactions	• University–industry interactions contributed to mobilizing resources for funding research and development activities where public funding was not widely available • Multi-stakeholder partnerships also contributed to mobilizing funding, often by reducing risks for private companies, such as in the case of the Nibe turbines
		Infrastructure	• Resource mobilization was a key function allowing the deployment of wind energy technologies, contributing to make wind energy a major source of electricity generated in Denmark

[a] See the Table 3 for the description of functions

[b] References to institutions as a structural element in this table are to systems of formal and informal rules.

Table 4. (continued) Structure-function coupled analysis of the Danish wind energy sector

Function[a]		Structural element	Interventions in the Danish wind energy innovation system
F6	Legitimation	Actors	- Scientists and local entrepreneurs were the first to use wind energy for rural development and energy access. They also showed that the technology worked and could indeed be integrated into the energy system - Independent experts and environmentalists provided legitimacy to wind energy by emphasizing it as the best alternative to nuclear energy and fossil fuels - The Government provided legitimacy to wind energy by making it a key component of the national energy plans
		Institutions[b]	- National energy plans including specific targets for wind energy generation contributed to wind being seen as a legitimate energy supply technology - Specialist publications contributed to legitimate Danish wind turbines by sharing information on their good performance
		Interactions	- Public hearings during planning processes contributed to the increased legitimacy of wind technology in energy planning - The 'Wind Meetings' helped to disseminate information about wind energy and its use as a viable solution for ensuring energy security in Denmark - Collaboration within wind cooperatives helped to increase awareness of the benefits of wind energy for rural areas, boosting the legitimacy of wind energy
		Infrastructure	- Dependency on foreign energy resources and the high availability of wind energy resources helped to lend legitimacy to wind energy technologies as a means of ensuring energy security and energy access in Denmark - Lack of reliable access to the national energy grid led rural communities to look for alternatives means of energy access and economic development
F7	Development of positive externalities	Actors	- Providing means for energy access and rural development to empower local communities was the main aim of the development of wind energy in rural Denmark by scientists and entrepreneurs
		Institutions[b]	- Strong community ownership in the Danish wind TIS ensures that wind energy also helps local communities to meet societal goals - Tax exemptions and subsidies increased revenues for cooperatives
		Interactions	- Actors concerned about rural development and environmental sustainability contributed to the formation of networks and associations that would then increase political support for wind energy - Collaboration between universities and industry had the clear aim of developing knowledge that would also be useful to technology users so that resource mobilization would be easier
		Infrastructure	- The deployment of wind energy allowed small rural firms to upgrade their production processes and provide more reliable energy access to rural communities - Wind energy development allowed Denmark to reduce international energy dependency by establishing a local renewable energy system - Wind energy played a key role in the decarbonization of the Danish electricity grid, while providing a more socially accepted alternative to nuclear energy

[a] See the Table 3 for the description of functions

[b] References to institutions as a structural element in this table are to systems of formal and informal rules.

6. Role of the case in Denmark's nationally determined contribution

As discussed in section 1, climate change mitigation goals have been an important driver for the wind energy sector since the 1990s, and wind energy targets have been increasingly ambitious since then to align with increasingly ambitious mitigation objectives.

Denmark's nationally determined contribution is submitted by the EU on the behalf of all of its member States and many of the energy and climate policies implemented in Denmark are transpositions of measures agreed at the EU level for all member States. The EU has a binding target of reducing GHG emissions by at least 40% by 2030 compared with 1990 levels.[65] Since 2013, the EU's GHG emissions have been split into two parts[66]:

- GHG emissions in all EU member States that are covered by the EU Emissions Trading System, with rules and targets set at the EU level

- Other GHG emissions, which fall under the responsibility of the individual member States in which they occur, but with differentiated targets also agreed at the EU level. Policies to address these emissions are a mix of EU harmonized policies and domestically developed policies

Electricity generators emitting GHG emissions are covered by the EU Emissions Trading System, while renewable electricity generators are not. Member States do have binding national renewable energy targets, however, laid down in EU legislation.[67]

At the national level in Denmark, the Climate Act approved in 2020 also sets more ambitious targets for the reduction of the country's total national emissions. It stipulates a 50–54% emission reduction for 2025 and a 70% emission reduction for 2030, compared with 1990, and climate neutrality by 2050. The Act establishes a rolling target-setting mechanism for five years, 10 years in advance.[68] The deployment of renewable energy, in particular wind energy, has widespread support as a means of meeting the Danish 70% emission reduction target. The development of large-scale wind energy solutions, including new offshore wind farms, is expected to play a major role in reaching this and future targets, in Denmark as well as in the EU.

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[65] Danish Ministry of Climate, Energy and Utilities (2019). Denmark's integrated national energy and climate plan under the regulation of the European parliament and of the council on the governance of the energy union and climate action. Available at https://kefm.dk/media/7095/denmarks-national-energy-and-climate-plan.pdf.

[66] Each part is covered by different legislation: the EU Emissions Trading System Directive (and its implementing legislations and delegated acts) and the effort-sharing regulation respectively. Denmark's domestic 2030 target for non-Emissions Trading System emissions amounts to –39% compared with 2005 levels. Source: effort-sharing regulation.

[67] Denmark's renewable energy in 2020 (as the share of renewable energy in gross final energy consumption) under the 2018 EU renewable energy directive amounts to 30%. Note that this is not limited to renewable electricity. Source: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=EN

[68] Grantham Research Institute on Climate Change and the Environment. Climate Change Laws of the World: The Climate Act. Available at https://climate-laws.org/geographies/denmark/laws/the-climate-act.

7. Key success factors and lessons learned

For successful innovation, both technology-push and demand-pull policies are needed.

The successful development of the wind energy innovation system in Denmark is the result of research and development and entrepreneurial experimentation efforts that have allowed wind energy technologies to generate electricity efficiently on the one hand, and of multi-level market creation policies that have generated the right incentives for developing commercial wind energy generation capacity and helped to create a market for renewable energy on the other.

A dynamic interaction and synergies between bottom-up and top-down measures facilitate innovation.

Bottom-up initiatives helped to better adapt wind energy technologies to local interests and needs, for instance in terms of energy access and economic development in rural areas. Nevertheless, on their own, these initiatives were not enough to make wind energy competitive in the market. Consistent and coherent government policies were crucial for setting up legislation to achieve this aim[69] and to establish long-term targets for wind energy, thus helping to shape expectations regarding the role of wind energy in the future Danish energy system. Importantly, it was the synergetic interaction between these bottom-up and top-down measures that provided the dynamism for innovation.

Coordination between knowledge producers and knowledge users accelerates technology development and diffusion.

The role of multi-stakeholder networks has contributed to the development of wind energy technologies in Denmark, be it in the early stages when pioneers engaged with local firms and communities to come up with energy-related solutions, or later via close industry–university collaboration. Specialist publications and the ‘Wind Meetings’ helped to promote knowledge-sharing and raise awareness of the high performance of Danish wind turbines, which facilitated their entrance into the global market.

Dynamic, evolving innovation systems continuously utilize and create new opportunities.

Challenges change over time and hence new solutions are needed on a continuous basis. A system that adapts to these changes will result in the development of new and/or better materials, products and services, thus creating new markets or expanding existing ones. In the wind energy sector this can be seen in the development of new materials, technologies and services in response to environmental concerns (wildlife endangerment, recyclability), stakeholder resistance (noise pollution, visual pollution), grid integration issues and financial risks. In terms of services, this may entail support for impact assessments and stakeholder engagement in the form of, for example, visualization tools, bird migration modelling, grid integration modelling and engineering, project management or finance application support.

Sustained government and public support can provide legitimation, altering institutional risk perceptions of a technology.

Institutional investors have long seen renewable energy generation plants as a risky investment owing to an unfamiliarity with the technology and related challenges. In contrast, in Denmark, the long-standing support for wind energy has resulted in a level of credibility for the sector that resulted in many pension funds in Denmark investing in wind energy owing to its widespread perception as a safe investment.

Individual champions can play an important role in driving innovation with regard to specific technologies.

As demonstrated by the role of meteorologist, inventor and science professor la Cour, individual scientists can play a significant role in research, development and deployment, knowledge development and diffusion, entrepreneurial experimentation, strengthening of local communities and realization of externalities (e.g. via the Askov Folk High School and D.V.E.S, and through energy access in rural areas).

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[69] Establishing, for example, subsidies, grid connection guarantees for wind parks, and obligations to purchase power from wind producers.

Aligning technological development to societal goals can facilitate the formation of coalitions that provide political support and legitimacy to new technology, while participatory approaches increase ownership and public acceptance.

The goals of energy security, energy access, rural development and environmental sustainability were behind the widespread public support that wind technologies had and have in Denmark. The strong role of cooperatives in the Danish wind energy sector as well as the participatory approaches to energy planning, relying on municipalities and local public hearings, have ensured strong public support for wind energy development. Public support facilitated the creation and implementation of additional policies that will further support the development of the TIS.

International aspects can influence the development of local innovation systems, intentionally or not.

Local support for technology innovation and early market formation increased the country's ability to compete in international markets. The oil crisis was a crucial turning point in Denmark's national energy planning, resulting in wind energy being prioritized as a renewable and environmentally sustainable alternative to oil and nuclear energy and as a means to ensuring national energy security and increasing prosperity in rural areas. Subsidies in California helped to create the first market for Danish wind turbines abroad. Later, increased concerns about environmental sustainability globally, including via the UNFCCC process, helped put wind energy even higher on the agenda and boost the global market for Danish wind turbines. Early public support, as well as bottom-up experimentation and learning, gave Denmark the initial advantage in the wind industry, and its systematic continuation and reformulation allowed to maintain its leading position.

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8. Good practices for potential replication

The above lessons learned led to the identification of the following good practices in the Danish wind sector that could be replicable in other countries.

Undertake continuous monitoring and evaluation activities, providing room for realignment actions with goals and adapting to evolving challenges and new opportunities.

The Danish Government has set multiple targets for wind energy generation, increasing ambition each time. This helped to shape expectations regarding the future role of wind energy. This good practice of establishing a long-term direction for the role of wind energy and thus providing certainty to technology developers and investors could be replicated in many different contexts, including for other technologies. Monitoring and adapting to newly emerging challenges not only is useful for preventing or reducing such challenges, but can also help to create new opportunities over time for new sectors and providers of materials, technologies, products and services.

Strengthen networks to ensure coordination between stakeholders.

Multi-stakeholder networks facilitate knowledge-sharing and coordination and the uptake of technology, be it through university–industry collaboration, public–private partnerships, or meetings and publications involving cooperatives and associations. This applies to a broad range of climate technologies.

Facilitate a combination of top-down and bottom-up measures.

Bottom-up initiatives promote higher community ownership and allow for alignment with local interests and needs. However, such initiatives often occur spontaneously, meaning they are not directed by government interventions. Policymakers can help to promote bottom-up initiatives by creating governance structures that allow for local decision-making, such as public consultation procedures. In addition, the Government should ensure that there are no regulatory or other barriers to local initiatives and cooperatives, for example enabling them to compete in the market. They can also ensure that local stakeholders are heard and have the capabilities necessary for coming up with creative local solutions and experimentation. Moreover, policymakers can guide the direction of technological change and ensure market access for new technologies by setting up supporting policies and regulations, as well as by mobilizing resources.

Ensure policies address both technology-push and demand-pull aspects.

Knowledge development, improving performance and experimentation with new technologies are crucial to ensuring the legitimacy of new innovations. However, new technologies are often unable to compete with established ones, or they are not yet integrated into regulations. Proactive policymaking is required to ensure these new innovations can become competitive in the market, for instance via subsidies, price premiums, and regulations allowing electricity to be sold back to the grid or ensuring grid connection. Moreover, by setting ambitious long-term targets, governments can help to create more certainty regarding the future demand for climate technologies.

Build trust in technologies to reduce risk perception and stimulate investments.

When private or public investors see a sector as low risk, they are more likely to invest in it. Long-term support from governments can help create legitimate sectors or technologies, resulting in increased credibility and reduced risk perception. This can be enhanced by broad support from the general public for the technology. Increased investments, especially by institutional investors such as pension funds, can in turn further increase credibility.

Leverage international developments.

Solutions to tackle national challenges can impact innovation in other countries. For instance, the creation of markets abroad in California helped the Danish wind industry to grow in scale. At the same time, technological improvements and cost reductions in the Danish wind industry have shown many other countries that this is a viable solution for meeting their climate change targets. The situation of policies in one country contributing to strengthening innovation systems in other countries can also be seen in other cases,


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for instance in the cases of photovoltaics in China[70] and bio-ethanol in Brazil (see the Brazil case study published by the TEC[71]). Benefits from innovation in certain countries, such as cost reductions, can often be seen globally given the internationalization of supply chains. Knowledge-sharing via transnational networks plays a role in this. However, this knowledge-sharing should cover not only technical aspects, but also policies and regulations that can promote certain innovations.

Ensure synergies between innovation policy and multiple societal goals.

Wind energy development in Denmark has been consistently driven by societal challenges, such as those related to energy access, rural development, energy security and environmental sustainability. These societal goals contributed to increasing public support for wind energy, resulting in the promotion of innovation and ambitious target-setting. Ensuring synergies between societal goals in innovation policy design can create enhancer effects, as achieving societal goals such as socioeconomic development and environmental sustainability can increase support for new policies in the future. Here, it should be noted that the situation of Denmark as a developed country is different in many ways to the situation in many developing countries. However, as the similar experience with the Brazilian bio-ethanol activities demonstrates, lessons and good practices may also apply in a developing country context.

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[70] See for instance Binz, C., B. Truffer, L. Li, Y. Shi, and Y. Lu, 2012: Conceptualizing leapfrogging with spatially coupled innovation systems: The case of onsite wastewater treatment in China. Technol. Forecast. Soc. Change, 79(1), 155–171, doi:10.1016/j.techfore.2011.08.016. and Gallagher, K. S., 2014: The Globalization of Clean Energy Technology: lessons from China. MIT Press, London, England, 261 pp.

[71] TEC (2023).

TEC

About the Technology Executive Committee

The Technology Executive Committee is the policy component of the Technology Mechanism, which was established by the Conference of the Parties in 2010 to facilitate the implementation of enhanced action on climate technology development and transfer. The Paris Agreement established a technology framework to provide overarching guidance to the Technology Mechanism and mandated the TEC and CTCN to serve the Paris Agreement. The TEC analyses climate technology issues and develops policies that can accelerate the development and transfer of low-emission and climate resilient technologies.

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Contact Details

The Technology Executive Committee may be contacted through the United Nations Climate Change Secretariat

Platz der Vereinten Nationen 1,
53113 Bonn, Germany
Email: tec@unfccc.int

Website: www.unfccc.int/ttclear/tec

UN Climate Change Technology Linkedin Group:
https://www.linkedin.com/groups/14126588/

#climatetech #TEC tclear/tec/NSI.html

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