Report 2023

Denmark

Risø Hybrid Power Plant. *Photo: Andreas Bro / DTU Wind and Energy Systems.*

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Denmark continues to be a global leader in variable renewable integration. 2023 was a record year for solar and wind energy generation, providing 64% of demand compared to 60% the year before[1].

The increase was mainly due to new solar parks whereas the wind share remained unchanged at 54%. However, the wind share is expected to increase in 2024 by 350 MW, with the connection of the offshore wind farms Vesterhav Nord and Syd.

In November 2023, the Danish and German TSO's, Energinet and 50Hertz, started the tendering process for key technologies of Bornholm Energy Island that will bring 3 GW of green power to German and Danish energy consumers. The next step will be receiving bids and starting negotiations until contracts can be signed in the second half of 2024.

The prioritisation of RD&D projects reflects wind energy becoming a dominant part of the energy system. It focuses on appropriate test facilities, reliable and cost-effective wind

[1] Energinet.

turbine technologies, system integration and Power-to-X (PtX). The impact of that investment was evaluated in 2023.

Highlight(s)

- Record year with 64% of total power consumption from renewable energy sources, of which wind power constituted 54.1%.
- Danish and German TSO's, Energinet and 50Hertz, started the tendering process for key technologies of the joint project, Bornholm Energy Island, expected to deliver a capacity of 3 GW.
- EUDP evaluation of R&D projects 2015-2022, in which wind energy had received the largest funding.

Table 1. Key National Statistics 2023: Denmark

Total (net) installed wind power capacity*	7.203 GW
Total offshore capacity	2.474 GW
New wind power capacity installed	0.036 GW
Decommissioned capacity (in 2022)	0.026 GW
Total electrical energy output from wind	19.54 TWh
Wind-generated electricity as percent of national electricity demand	54.1%
Average national capacity factor	31.4%
Targets	55% renewable energy by 2030 ~100% renewable power by 2030 Phase out coal by 2030 70% CO2 reduction by 2030 Phase-out fossil fuels by 2045
National wind energy R&D budget	DKK 167.7 million (USD 24.1 million)

* Energinet.

Market Development

Targets and Policy

In accordance with the Energy Agreement from 2018, the national target for renewable energy is to provide 55% by 2030, equivalent to more than 100% renewable electricity exporting green power to neighbouring countries, and to phase out coal in the energy system. In 2011, the Danish government set a target be climate neutral by 2045.

The Danish government aims to quadruple onshore wind and solar capacity by 2030 in anticipation of a 50% rise in electricity needs. The plan involves offering residents near projects a greater share in profits and creating energy parks with simplified permitting procedures. The government will identify areas with energy potential and eliminate regulatory hurdles to fast-track renewable projects. This initiative aims to streamline processes and involve local communities to accelerate the energy transition [1].

In April 2023, the government presented a plan to reserve 30% of sea area for wind turbines. This means that it will be possible for developers to build more turbines per square metre of sea area than before, the so-called over-planting.

Later in 2023, the government presented a political agreement on the framework conditions for 9 GW of offshore wind in Danish waters by 2030 and the possibility of over-planting. The bidders participate in the tenders by offering a fixed annual concession payment to the state over the course of 30 years for the right to use the offshore area. For the first time, the Danish state will be co-owners of the offshore wind projects with a state ownership share of 20% of the tenders for 6 GW of the wind projects[2].

Progress and Operational Details

Record high production from wind and solar energy in 2022. The power production from wind and solar was 64% of total power consumption, compared to 60% in 2022. The increase was mainly due to new solar parks while the share of wind energy remained at 53.4%. The figure below shows that wind power in the first nine months of 2023 was 1.6% lower that the corresponding period last year, but it was still 13.8% higher than the average over the five previous years.

Wind energy in 2023. Denmark installed 34.5 MW of wind energy in 2023, of which test turbines represent 30.9 MW. Small household wind turbines under 25 kV are not included. This means that only one commercial wind turbine with a capacity of 3.6 MW was installed [2].

[2] Denmark's largest tendering procedure for offshore wind power is launched | Danish Energy Agency (ritzau.dk)

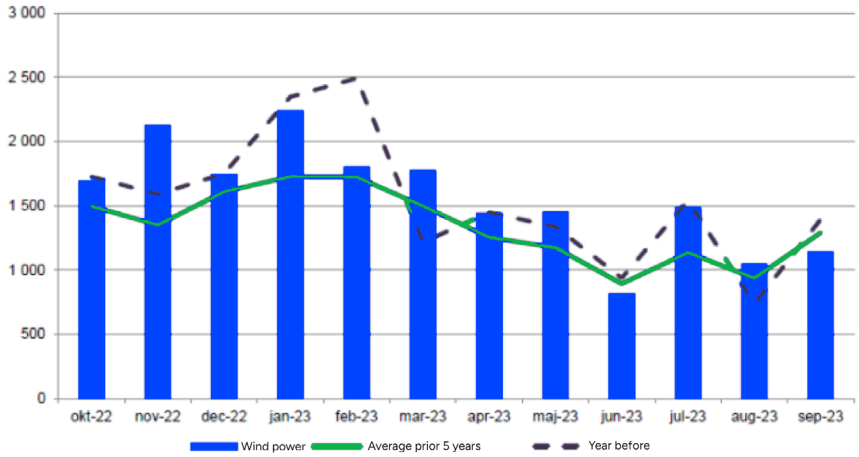

Figure 1. Wind power production, GWh. *Source: Energistatistikken for de første ni måneder af 2023.*

New procurement model for counter trade. In previous years, up to 1,000 GWh from Danish wind energy production was curtailed due to bottlenecks in the German grid. A new countertrade model has changed this and curtailment is estimated to be down to 0-10 GWh in the second half of 2023. Countertrade means a cross-zonal exchange initiated by system operators between two bidding zones to relieve physical congestion. This model is therefore used when the Danish TSO, Energinet, buys or sells energy in DK1 and DK2 to relieve bottlenecks in the electricity grid at the request of a neighbouring TSO [3]. An integrated intraday market promotes effective competition and pricing, increases liquidity and enables a more efficient utilisation of the generation resources across borders. With the increasing amount of fluctuating production, it becomes challenging for market participants to be in balance after the closing of the DayAhead market. Being balanced on the network closer to delivery time is beneficial for market participants and for power systems alike, for example, by reducing the need for reserves and associated costs.

Wind energy outlook 2050. The Danish Energy Agency published its analytical assumptions for the future energy system up to 2050, which account for the pipeline of new projects, political agreements, and technological development. For onshore wind, the agency expects a substantial expansion of onshore wind in combination with decommissioning and repowering the old wind turbine fleet [3]. For offshore wind, the development is ambitious, aiming for 45 GW by 2050. This includes energy islands and offshore hydrogen wind energy [4].

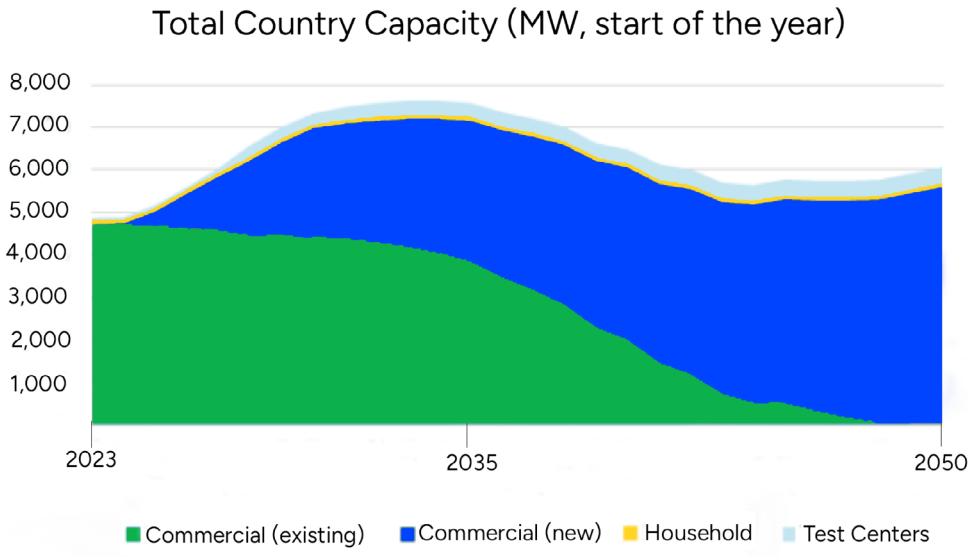

Figure 2. Total onshore wind capacity (MW). *Source: Analyseforudsætninger til Energinet 2023 – VE på land (sol og landvind).*

[3] https://energinet.dk/media/3q2pb13l/methodology-for-procurement-of-countertrade-energy-with-accepted-changes.pdf

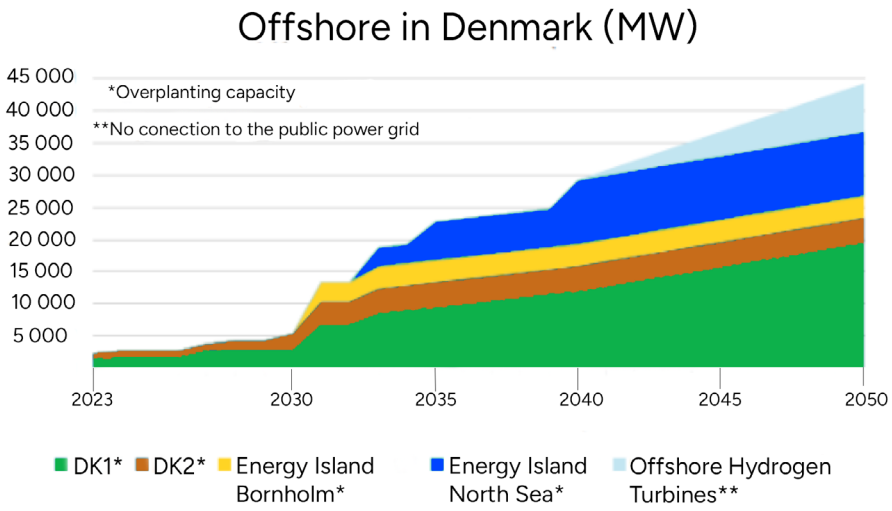

Figure 3. Total offshore wind capacity (MW). *Source: AAnalyseforudsætninger til Energinet 2023 - Havvind.*

The Viking Link. A new interconnector was installed and tested in 2023. The 1.4 GW Viking Link HVDC subsea cable, the world's longest interconnector spanning 1,400 km from Denmark to the UK, connects West Jutland in Denmark to the Bicker Fen substation in Lincolnshire, England. Viking Link was officially inaugurated in April 2024 with the goal of enhancing electricity markets across the two countries and reducing congestion.

Figure 4. Viking Link Inauguration, April 2024.

Baltic Energy Island. In June 2023, the German and Danish Governments signed a legally binding agreement to develop the Bornholm Energy Island project which will deploy at least 3 GW of offshore wind in the Danish Baltic Sea. TSOs, 50Hertz and Energinet, will work together to set up an electricity hub and install 525 kV DC submarine and land cables, providing offshore wind power to both countries. 50Hertz has signed a contract for the procurement of HVDC cables for Bornholm Energy Island and several other projects. Energinet has started the tender of one contract for production of cables as well as offshore installation. Onshore installation and horizontal directional drillings (HDD) will have a separate contract. In addition, surveying and removal of unexploded ordnance (UXO) will also be tendered as a separate contract at a later time. Civil works and the buildings for the HDVC stations will be tendered for Denmark and Germany respectively, at a later time. Construction on Energinet's part of the project in Denmark will start once it has received an environmental permit and archaeological excavations have been completed in 2025. In Germany, installation and construction can start after permits are granted by the authorities.

The energy island in the North Sea. For economic reasons, the government has decided to postpone its decision to invite tenders for the North Sea Energy Island as an artificial island. The reason for the decision is that an artificial island will likely be too expensive and risky for the state. Analyses from the Danish Energy Agency show that the state may have to pay up to DKK 50 billion (USD 7.3 billion) for the entire artificial island project. Due to the profitability of the project, the Danish government will investigate and research more cost competitive options to develop an energy island in the North Sea. An energy island is a hub for aggregation and distribution of largescale offshore wind. In a Danish context, an energy island also connects energy markets via an

interconnector. An energy island is not a specific concept and can e.g. also consist of platforms, which is one of the possibilities that will be investigated in the coming analysis [4].

First Power-to-X tender. The Danish Energy Agency finalised its first Power-to-X tender, awarding state aid to six projects, totalling 280+ MW of electrolysis capacity. The winners included Plug Power, European Energy, Electrochaea, and HyProDenmark/Everfuel. The tender opened in April 2023 and attracted major interest, with bidding companies applying for over three times the DKK 1.25 billion budget (USD 180 million). The State Aid was approved by the European Commission and consists of a direct grant to the winning bidders for a ten-year period.

RD&D Activities

National RD&D Priorities and Budget

The Danish RD&D funding landscape relevant to wind energy consists of The Energy Technology Development and Demonstration Programme (EUDP) and Green Labs Denmark. Both are administered by the Danish Energy Agency, and Innovation Fund Denmark (IFD). In addition, the Independent Research Council supports wind energy-related research. Further, private foundations and the industry itself finances wind energy RD&D, which is not accounted for here.

In June 2023, an evaluation of the EUDP project portfolio was published, covering all projects completed between 2015 and 2022. A total of DKK 3.3 billion (USD 480 million) was granted to 565 projects and supplemented by DKK 3.2 billion (USD 460 million) in co-finance. 78% of all projects were highly successful. The most important impacts were increased investment in technology development (81%), increased access to external competences (64%) and good frameworks for project consortia and partnerships (67%). Furthermore, the projects have all contributed to the national targets of the energy transition [5].

New RD&D projects. In 2023, EUDP supported nine new wind power projects with DKK 88 million (USD 12.67 million) or 16% of the total DKK 543 million (USD 78.2 million). Green Labs Denmark supported "Wind turbine main bearing test facility" at LORC with DKK 80 million (US 11.52 million) [6].

Danish Alliance for Renewables. The former Megawind has changed name, but is still the national strategic platform for research, innovation, test and demonstration for the future energy system. Wind and solar technologies are well established. However, there is still need for RD&D to cope with global trends such as zero-carbon energy systems, large scale solar and wind, often in combination with other technologies (e.g. electrolysis, Power-to-X, batteries), global markets and fierce competition, new business models and partnerships, social and environmental sustainability, and geopolitical instability. This public-private partnership outlines four research and innovation priorities: 1) Competitiveness; 2) Sector integration and electrification; 3) Resilience and security; 4) Circularity and sustainability [7].

Wind Turbine Test Centers. In December 2021, a broad majority in parliament agreed to further develop the Danish test centres with prototype wind turbines and establish more test pads for large wind turbines (up to 450 metres). During 2022-2023, further investigations were undertaken to identify suitable sites for a third test centre which became an extension of Østerild Test Center. Further environmental and habitat assessment will be conducted over the next 1.5-2 years [5].

National Research Initiatives and Results

Below is a small extract of the many projects that have received funding from EUDP. The first has been successfully completed and the other projects have just started, following a proper assessment based on expected impact and commercial results, in addition to a well-organised work plan, strong project management and a competent consortium.

- **ACOMAR – Auto Compact Marine Growth Remover.** (2020-2023). EUDP granted DKK 15.36 million (USD 2.21 million) to Sub C Partner and others to develop and demonstrate a subsea robot, ACOMAR - Auto COmpact MArine growth Remover. A prototype was successfully developed with a compact design allowing for the estimation and removal of marine growth. The technology is based on a high degree of automation and a special focus on developing methods for locating and controlling the ACOMAR in offshore conditions. The technology is tested in the North Sea and the results compared with the conventional methods for estimating and removing marine growth. SubC Partner was nominated for Innovation Project of the Year 2024 by Energy Cluster Denmark [6].

- **Extra-large 3D printed wind turbine towers produced on site on demand.** 2023-2027. EUDP granted DKK 30.5 million (USD 4.39 million) to the project, in which COBOD International A/S, Rambøll, Holcim Innovation

[4] https://www.en.kefm.dk/news/news-archive/2023/jun/the-concept-of-energy-island-north-sea-will-be-examined-thoroughly-

[5] Faktaark_vedr._aftale_om_miljoe-_og_habitatkonsekvensvurdering_ved_OEsterild_Testcenter_01.02.2024.pdf (blkm.dk)

[6] SubC Partner Nominated for Innovation Project of the Year 2024!

Center, Per Aarsleff A/S and DTU Construct collaborate to create extra tall onshore wind turbine towers using 3D construction printing. A structural design for 160 m tall hybrid towers will be developed, with the first 80 m being 3D printed and the remaining height either being 3D printed concrete or a steel tower. The existing BOD XL 3D printer model will be improved, enabling it to print 20 m tall tower bases with fiber reinforcement, at an industrial scale. A scaled model design will also be developed for testing and data extraction. The project will establish a design and construction method for 5 m tall 3D printed concrete rings to be stacked and put on top of the first 20 m base printed directly on the foundation. A 3D printable, fiber-reinforced, low-carbon concrete at an industrial scale, will be developed. A 6 m tall scale prototype is planned to be 3D printed in 2025 for general design and concept verification. If successful, the data collected will enable a follow-up project: building a complete prototype 161 m tower with a 5 MW wind turbine generator based on verified technical feasibility and cost savings. This project will focus on developing and validating the structural design, material design, and printing technology [7].

- **WISEWIND (neW generatIon of SustainablE WIND turbine Blades).** 2023-2026. Innovation Fund Denmark granted DKK 8.52 million (USD 1.23 million) to DTU, Siemens-Gamesa and Reflow to tackle the waste issue from wind turbine blades and reduce the CO2 emissions. The project aims to provide the material basis for a new type of wind turbine blades that are fully recyclable and will be easily separated into high performance glass fiber and polymer resin. The project will develop a computational model and digital twin of the wind turbine blade composites from cradle to grave. This model will support the adjustment of curing profiles limiting residual stresses and ensuring the best fatigue properties for the blades. The model will also provide processing conditions for the recycling processes using several techniques. To validate the sustainability of the new resin, environmental impacts will be characterised, a cost analysis will be performed and additional social parameters will be quantified [8].

- **SilentEdge.** 2023-2026. EUDP granted DKK 7.65 million (USD 1.1 million) to Power Curve, DTU and Statkraft to develop a trailing edge serration product for wind turbine blades that offers increased noise reduction features. The serration product will be available as a load neutral add-on for existing wind turbines [9].

Test Facilities and Demonstration Projects

Denmark continues to invest in research and test facilities for the wind and energy system. The National Energy System Facility (NEST) – a research infrastructure for the development of energy system transition – was approved and supported by the Danish National Committee on Research Infrastructure, NUFI.
An overview of the most important facilities is shown in the table below.

Test Centre Høvsøre, West Jutland	Offers seven testing sites for international companies to test their wind turbine concepts and collect data from tests carried out on the turbines. It is possible to test and document safety, the turbine's performance, and noise emissions up to 200 m in overall turbine height. Test Centre Høvsøre (dtu.dk)
Test Centre Østerild, West Jutland	Offers state-of-the-art facilities to test up to nine wind turbines, of which Vestas owns two, Siemens Gamesa two, and DTU Wind Energy the remaining five test sites. It is possible to test turbines up to 330 m in five of the test sites and up to 250 m for the remaining sites. It is currently investigating how to increase the max height to 400 metres. Test Centre Østerild (dtu.dk)

[7] Ekstra høje 3D printede vindmølle tårne produceret på installationsstedet | EUDP

[8] WiseWind neW generatIon of SustainablE Wind turbine Blades | Energiforskning

[9] SilentEdge – Optimerede serrations til vindmøllebagkanter til reduktion af vind-møllestøj | Energiteknologi (energiforskning.dk)

The National Energy System Transition Facilities (NEST)	NEST is a national network of Risø Hybrid Power Plant Facility, PowerLab, Østerild Test Center, Green Lab Skive, an electrofuel laboratory in Foulum, a PtW laboratory and a microgrid test laboratory at AAU. It aims to consolidate and enhance the capabilities of various existing energy and power system labs across Denmark. By focusing on specific segments of the energy transition, such as wind and solar power generation, power-to-x technologies, and the integration of energy production and demand, each NEST facility contributes a unique piece to the puzzle. NEST has the ambition to virtually connect individual setups or entire labs, transcending power and technology readiness levels, and geographical barriers. This interconnected approach will enable the execution of research and demonstration projects at scales that were previously unattainable.
PowerLabDK Facilities, DTU	PowerLabDK includes a number of state-of-the-art facilities linked through communication systems, SCADA-solutions etc. across four locations. The facilities are capable of testing and demonstration according to a variety of international standards, including IEC, CENELEC, IEEE and others. PowerLabDK Facilities - DTU Wind and Energy Systems
AC/DC Wind Power Laboratory, DTU Risø Campus	A converter-based laboratory aimed at investigating power electronic controls and controller interactions in low-inertia systems. It consists of four 10 kW custom-built converters. Two of them are 2-level converters, and two are MMC (modular, multi-level converters), covering the main converter technologies used today.
Risø Hybrid Wind Plant Facility, DTU Risø Campus	Risø Hybrid Power Plant Facility is currently under development. By the end of 2024, it will consist of a 2 x 225 kW wind power plant which is connected to the grid together with ~1000 kWh storage technologies and a 2 x~ 200 kW solar PV plant, and a distribution board interconnecting the system. The two 225 kW pitch-controlled wind turbines are retrofitted with Danfoss power converters and wind turbine controllers supplied by Emerson Wind Technologies (former Mita-Teknik). Initially, Risø HPP will be connected directly to the Radius utility grid, but the grid connection will soon be advanced with a Controllable Grid Interface (CGI) which makes it possible to test the real Risø hybrid power plant connected to an open model emulated grid.
The Large-Scale Facility, DTU Risø Campus	The facility consists of a 1,560 square metre test hall with three test stands capable of testing 45 m, 25 m and 15 m blades or other slender structures. Large Scale Facility - DTU Wind and Energy Systems
Poul la Cour Wind Tunnel, DTU Risø Campus	The Poul la Cour Tunnel is a wind tunnel of the closed-return type. The fan is driven by a 2.4 MW motor, giving a volume flow of up to 630 cubic metres per second, corresponding to a maximum test section velocity of about 105 m/s or 378 km/h. Poul la Cour Wind Tunnel - DTU Wind and Energy Systems
Composite Laboratories, DTU Risø Campus	Composite lab for R&D within hybrid processing techniques, preparation of test specimens, accredited mechanical testing to meet industrial standards, X-ray computed tomography, electron microscopy, plasma treatment, and surface chemistry, sensor instrumentation, and signal analysis. Material Laboratories - DTU Wind and Energy Systems
The research wind turbine V52 DTU Risø Campus	The research wind turbine is a variable speed-pitch adjusted wind turbine and works as the main part of the large modern megawatt wind turbines. The research wind turbine V52 - DTU Wind and Energy Systems

WindScanner, DTU	Windscanner.dk was established in 2010 to provide the European wind energy research community and industry with remote sensing-based wind scanners, able to map the entire 3D wind fields around today's substantial wind turbines, wind farms, bridges, buildings, forests, and mountains. WindScanner - DTU Wind and Energy Systems
Leading-Edge Erosion Test Facility, DTU Risø Campus	The Facility is an evolving platform for development, offering non-standard options that push the boundaries of conventional testing: Enhanced Rain Flow: increased rain flow capabilities of up to 400 l/h, surpassing the standard 120 l/h, allowing shorter testing times at tip speeds matching turbine conditions. Dual Independent Droplet Manifolds: with the standard 600 and expanded 1,200 needles droplet manifolds, the facility offers unmatched precision in simulating diverse weather conditions. Expanded Heat-pump System: The facility boasts a powerful 50 kW thermal heating and cooling system, allowing better testing stability and possibility for testing different climate conditions. Leading-Edge Erosion Test Facility - DTU Wind and Energy Systems
Lindø Offshore Renewables Center (LORC)	Lindø Nacelle Testing is located in two adjacent buildings. The 14 MW and 16 MW test facilities are located in a 3,500 square metre test hall, and the larger 25 MW test facility is located in a 2,250 square metre test hall. https://www.lorc.dk/test-facilities

Figure 5. Offshore expansion 2023.

Collaborative Research

The Danish Energy Agency supports Danish companies, universities, and research institutions directly or via international cooperation schemes when participating in international projects. This includes financial support for participating in the IEA TCPs and indirectly by means of common calls in the EU (ERA-net scheme) and Nordic Energy Research. Denmark participates in most of the IEA Wind TCP Tasks.

In February 2024, the Innovation Fund Denmark and the US Department of Energy announced an upcoming USD 4.2 million to advance floating offshore wind energy systems towards cost-effective commercialisation and wide-scale deployment*.

Impact of Wind Energy

Environmental Impact

CO2 emissions. There has been a significant decrease in emissions from the electricity and district heating sector. Until 2010, it accounted for 30-40% of total Danish emissions, but in 2021, the share dropped to only 11% of total emissions. This share is expected to fall to 3% by 2025, and in 2030 electricity and district heating will comprise less than 1% of net total emissions. The reduction is primarily due to phasing out the remaining coal-fired CHP plants, continued deployment of wind and solar PV, as well as significant heat pump deployments for district heating [8].

A new marine nature fund, 2024-2030. As part of the political agreement for the framework conditions for tendering 9 GW in offshore wind, DKK 500 million (USD 72 million) was earmarked for a new marine nature fund. Its mission is to contribute to knowledge about the environment, the environmental impacts of large-scale renewable energy in Danish waters and a cost-effective restoration of marine nature and biodiversity.

Strategic screening of offshore wind potential 2022-2025. In 2022, the Danish Energy Agency allocated resources for a strategic environmental screening of offshore wind in Danish waters. Its purpose is to collect the necessary environmental data and to support the long-term planning and decision-making of large-scale offshore wind in Denmark. The project maps the areas potentially vulnerable to large-scale offshore wind. As part of the screening, the Danish Energy Agency, together with The Geological Survey of Denmark and Greenland (GEUS), are conducting geological mapping of the Danish seabed. This will be decisive for identifying the optimal location of offshore wind turbines. Further, the engineering consultancy company, NIRAS, Aarhus University and DTU Wind will provide technical assistance and advise the strategic environmental screening of the offshore wind potential.

Economic Benefits and Industry Development

Job creation. The wind energy industry employes ~33,000 full-time equivalents. However, in order to comply with the ambitious Danish targets and policies for the green transition, various studies have demonstrated that for the period 2023-2030 an additional 45,000 full-time equivalent employees are needed on average each year. The job demand is particularly necessary for offshore wind and Power-to-X, where considerable investments are expected. This makes the green energy industry call for action. Recommendations include 1) a short- and medium-term plan for how to develop competent employees; 2) strengthen technical educations at both universities and vocational colleges; 3) International recruitment; 4) attractive conditions for seniors; 5) flexibility and continuing education; 6) diversity [9].

Export. The export of Danish energy technology decreased slightly in 2023 to DKK 109.2 billion (USD 15.72 billion), of which wind technology and its related services constituted 43.7%. For wind energy technologies, the export in 2023 decreased 7.4% to DKK 43.7 billion (USD 6.29 billion), covering wind technology equal to. DKK 37 billion (USD 5.33 billion) and its related services of DKK 6.7 billion (USD 0.96 billion) [10]. Export of wind energy technology to other European countries decreased to DKK 20.6 billion (USD 2.97 billion) or 9.4%, but less to non-European countries with DKK 16.4 billion (USD 2.36 billion) or a decrease of 6.6%. The top five export countries were Germany (16.9%), the United Kingdom (10.5%), France (8.5%), the United States (7%) and the Netherlands (5.4%).

Next Term

A 15 MW Vestas wind turbine is under installation in Thyborøn. It is owned by Thyborøn Sydhavns Møllelaug II and its 2,800 stakeholders in the municipality of Lemvig. Although it is very visible on the landscape, there have been no complaints at all due to local engagement **.

One year after the political agreement, the Danish Energy Agency announced in April 2024 a tender for 6 GW offshore wind energy in Danish waters. This will multiply Denmark's offshore wind production in the coming years with a new offshore wind tender of up to 10 GW by 2030. The 6 GW will be divided into : a minimum of 3 GW in the North Sea I (divided into three farms); a minimum of 1 GW at the Kattegat; a minimum of 1 GW at Kriegers Flak II; and 0.8-1.2 GW at Hesselø.

* DOE and Innovation Fund Denmark Announce Upcoming $4 Million Opportunity to Advance Floating Offshore Wind | Department of Energy.

**Verdens bedste vind, verdens største laug, verdens største mølle | Green Power Denmark.

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