Success Stories | Denmark | Electricity

VARIABLE RENEWABLE ENERGY GRID INTEGRATION

KEY TAKE-AWAYS

Since 2019, **over 50 percent** of Denmark's power has come mainly from **wind**, onshore and offshore, and **solar**. These renewable energy sources are weather-dependent and provide **fluctuating** energy supply. In comparison, the EU average share of variable renewable energy in 2021 was 19 percent.[1] **In all, over 75 percent of power** in Denmark comes from **renewable energies**[2]. Denmark aims to reach a fully renewable-based power system by 2030, increasing further wind and solar capacity.

Denmark has made **pioneering changes to its power system** to maintain continuous service in the face of rapid and large swings in electricity generation from wind and solar. All aspects of the power system, from real-time **operations** to long-term system **planning**, fundamentals of **supply** and **demand,** power system **market design** and **infrastructure** development have evolved over time to support and increase the system's **flexibility** and integrate **ever-higher shares of fluctuating wind and solar generation**.

1 Ember (2022).
2 Data from 2021, Ember (2022).

The country's **strategy** for increasing power system flexibility relies on five **key measures**, which were initiated in the following order: (1) increasing the **flexibility of existing power plants**, (2) expanding cross-border **interconnectors** and **trade**, (3) investing in the remaining combined-heat-and-power (CHP) plants, **heat pumps** and **heat storage** to serve as source of **flexibility**, (4) improving wind generation **forecasting**, and (5) making consumer **demand** more **flexible**.

Denmark has achieved the transformation of its energy system while maintaining **steady economic growth** and has become one of the world's most **energy-efficient** economies in the process.[3] In addition, **greenhouse gas emissions** from the **energy supply sector fell** dramatically **by 72 percent** between 1990 and 2020 and reached 25 percent of national emissions in 2020.[4]

3 Danish Energy Agency (2016).
4 EEA (2022a).

OVERVIEW

The **transformation of the Danish energy system** started in the late 1970s in response to the oil price crisis. After an initial focus on **energy efficiency**, the government also turned to renewable energy, adopting in 1981 its **first target for wind energy expansion**, 1,000 MW of installed capacity by 2000. Denmark exceeded this target by a wide margin, achieving 2,390 MW of installed capacity in 2000,[5] and generating 4,241 GWh of power.[6] Beginning in 1984, the expansion of wind energy was supported by the world's first **feed-in tariff scheme**.[7] Wind capacity grew steadily, almost doubling from 2000 to 2010 and more than doubling again, along with **solar**, from 2010 to 2020 to reach altogether 50 percent of power generation.

5 IEA (2017), p. 76.

6 IEA (2022).
7 Kapervicius and Balezentis (2022).

Over the last few years Denmark has increased its **climate ambition** twice, pledging to **accelerate the expansion of wind and solar capacity**. In 2022, in response to the energy and security crisis, the Danish government decided to go beyond covering domestic energy needs and **provide electricity to Europe**. To this end, Denmark will accelerate its **energy island projects**, electricity hubs from offshore wind farms in the North and Baltic seas.[8]

Sustained **investments in flexibility, interconnection and grid management** have resulted in a transmission grid that absorbs increasing shares of variable renewable energy sources (RES) while also fully preserving system reliability. Denmark has one of the **lowest average power outage duration** in Europe.[9] Future challenges include the **activation of flexibility potentials on the demand side** e.g. via the management of electric **vehicles charging** and **heat pumps use** based on power availability, measures to synchronise renewable energy development and **grid expansion** as well as the implementation of **long-term storage** solutions and **green hydrogen** production.[10]

With the acceleration of the pace of the green transition and increased political ambition, Denmark is shifting from a carefully planned and incremental transition roadmap to a **shared vision** and agreement on the necessary **operational changes** and their **order of priority** for shaping the energy systems to support a power grid fully based on renewable energy.[11]

8 EnergyWatch (2022)
9 Danish Ministry of Energy, Utilities and Climate (2018), p. 15.
10 Ea Energy Analyses (2015).

Co-benefits

- → **Wind energy technology** has become a major source of **jobs** and a key industry, accounting for **10 percent** of Danish **exports** in 2015.[12]
- → **Security of electricity supply** has increased due to the use of domestic RES in parallel with a **reduced reliance on fossil fuels**.[13] The share of coal in electricity generation dropped from around 90 percent in the 1990s to around 50 percent in the 2000s and 10 percent in 2019.[14]
- → After recent reforms to the funding model for renewable energy, Danish **businesses** have now access to some of the **lowest electricity prices** in the **EU**.[15] Moreover, the availability of green power at a competitive price has lured foreign investment to Denmark, particularly for the construction of data centres.[16]

11 Energinet (interview, 2022).
12 Danish Energy Agency (2016).
13 Danish Energy Agency (2015).
14 IEA data (2022).
15 Danish Ministry of Energy, Utilities and Climate (2018), p. 29.
16 Danish Ministry of Energy, Utilities and Climate (2018), p. 23.

AIMS & TARGETS

In 2019, the Danish parliament set the ambitious goal of producing electricity solely from renewable energy sources, or a **100 percent-RES power system, by 2030,**[17] thereby moving forward by five years the target for full decarbonisation.[18] Additional capacity will mainly consist of **solar and wind energy**. Denmark's early investment in the energy system's flexibility allowed it to increase the share of variable power generation from 12 percent in 2000 to 22 percent in 2010 and 50 percent in 2020.[19] To achieve these milestones, Denmark developed **five main**

17 Danish Ministry of Climate, Energy and Utilities (2019).
18 Agora Energiewende and DTU Management Engineering (2015).

19 Danish Energy Agency (2021).

flexibility measures, listed in chronological order, reflecting when they were first introduced. However, implementation periods have overlapped, and measures have escalated in intensity over time as the share in variable RES increased.[20]

1. **Flexible thermal power plants through shifts in operation.** Between 2000 and 2015, i.e., when the variable RES share was below 20 percent, thermal power plants were induced to move from providing baseload to becoming a source of flexibility, mainly through **changes in operation**.[21] This applied in particular to the country's large fleet of combined-heat and power plants (CHP) which moved from a focus on heat production to become a **flexible power producer** in the 2000s. To allow for fast adjustments when wind energy supply changes, shifts between electricity-only and CHP modes of operation and increased ramping rates were encouraged. Incentives for these changes in operation came from the power market with **hourly price** changes, including the possibility of **negative prices**, established in 2009.

2. **Utilisations of interconnectors.** Cross-border trade via interconnectors was increasingly used to **balance intermittent wind production** in the years between 2010 and 2015 and further intensified as the variable energy share continued to rise. In 2021, Denmark had a total interconnector capacity of 6–7 GW, similar to the size of its installed wind and solar capacity.[22] A **regulatory framework** for allowing **cross-border electricity trade** was put in place early on. Denmark joined the Nordic power market **Nord Pool** in 2000, which became a role model for EU-wide market integration. The introduction of European **day-ahead trading** in 2015 and **cross-border intraday trading** in 2018 were other key milestones.
   Cross-border trade increases the balancing area available for matching power demand and supply. Imports and exports provide flexibility to the Danish system. They help to **avoid the costly curtailment** of excess wind energy and **reduce** the need for **back-up capacity**. The bigger geographical zone helps to smooth out variability in the generation patterns of RES plants. It also increases the diversity of the generation mix. In the Danish case, it integrates Danish variable wind energy with dispatchable hydropower resources in Norway and Sweden.[23]
   From the mid-1990s to the mid-2000s, Denmark was a **net importer** of electricity, but became a **net exporter** in the 2010s. From the 2020s onwards, as the share of variable renewable energy increases in the EU, the relative value of interconnections as a tool for flexibility in the Danish system is expected to decrease.

3. **Increased flexibilization and sector coupling through additional investments.** In the 2010s, the variable energy share started to exceed 20 percent and required further flexibilization of the energy system. The aim was to enable the **decoupling of heat and electricity production**. Investments in the remaining CHP plants were made to allow for **complete or partial turbine bypass and heat storage**, in combination with using **waste heat** into the existing **district heating** system. In addition, as the number of CHP plants was gradually reduced, they were replaced or supplemented by **heat pumps**.

4. **Forecasting and scheduling systems.** In order to better predict wind generation, thereby allowing for the early identification of upcoming imbalances between supply and demand, **forecasting tools** were improved. Better forecasting also allowed **wind energy** to participate in **balancing markets** for the first time in 2020.[24] On the market side, new information gained through the fore-

20 Danish Energy Agency (2021).
21 Ea Energy Analyses (2015).
22 Danish Energy Agency (2021), p. 12.
23 Danish Energy Agency (2021), p. 67.
24 Danish Energy Agency (2021), p. 54f.

casting tools was used by operators to further adjust their trading volumes very close to the time of delivery, thus increasing **intra-day trading**, a key flexibility enabler.

5. **Demand-side flexibility.** Since 2020, Denmark has been developing demand-side flexibility measures, including improved **consumer involvement** and innovative business models. New "sector coupling" technologies such as **power-to-heat**, **electric boilers**, **heat pumps** and **electric vehicles** will be used to absorb electricity generation when it exceeds demand. Prerequisites for these new options are the roll-out of **smart meters**, completed at the end of 2020, and the establishment of a **central IT system** to collect and process customer data. Called 'DataHub', it is owned and operated by the Danish transmission system operator (TSO), Energinet.[25] Moreover, in 2020 Danish regulators introduced the new market role of **aggregator**, an intermediary enabling households and smaller entities to take part in the power and balancing markets by bundling them together and controlling devices remotely.

25 See https://en.energinet.dk/energy-data/datahub/

On its way beyond 50 percent to 100 percent RES, Denmark plans to **intensify demand-side flexibility options and sector coupling**.[26] Moreover, the transmission system operator Energinet is working on improving the integration between **renewable energy build-up** and **grid expansion**. In September 2020, it developed a capacity map[27] used for **dialogue** with RES developers and municipalities in the choice of RES production sites and associated grid developments. As the lead time for grid development is higher than for RES project development, **anticipating future needs** is key.[28]

26 Danish Energy Agency (2021).
27 See www.kapacitetskort.dk.
28 Energinet (2021).

POLICY INSTRUMENTS

Energy sector transformation in Denmark has benefited from **continuous policy support** and a **strong consensus** among key stakeholders.[29] Key national and European policy instruments include:

- **The Energy Strategy 2050.** Adopted in 2011, the strategy sets out Denmark's overarching goal of gaining complete independence from fossil fuels across all sectors and it defines a number of concrete measures as steps forward.[30]
- **Denmark's Promotion of Renewable Energy Act.**[31] The Act provides support for wind power, by specifying that the developer and the distribution system operator share the cost of connection. It also includes a green scheme with subsidies for onshore wind turbines.
- **Denmark's Energy Supply Act.**[32] This act's main goal is to promote the use of sustainable energy. It applies to the production, transport, trading and supply of electricity, both onshore and offshore.
- **Danish Climate Agreement for Energy and Industry of 22 June 2020.**[33] This agreement increases the tax on fossil space heating to promote greener forms of heating. It also abolishes the electric heat

29 Agora Energiewende and DTU Management Engineering (2015).
30 Agora Energiewende and DTU Management Engineering (2015).
31 Danish Ministry of Climate, Energy and Utilities (2013a).
32 Danish Ministry of Climate, Energy and Utilities (2013b).
33 IEA (2021).

tax, making it easier to use green wind power for heating.[34]

→ **EU Capacity Allocation and Congestion Management (CACM) Guideline.** The EU regulation is regarded as a key legislation in the establishment of a common regulatory framework for free electricity exchange between EU Member States. It defines the tasks of the Nominated Electricity Market Operators (NEMOs) and provides capacity calculation methodologies.[35]

→ **The EU Network Code "Requirements for Generator" (RfG)** details technological specifications for wind turbines, improving how they support system stability.

34 Danish Ministry of Climate, Energy and Utilities (2020).

35 European Commission (2015).

ACHIEVEMENTS & LESSONS LEARNED

Pushing the boundaries

→ In 2021, the Danish power system absorbed a **54 percent share of variable energy from wind and solar** plants while maintaining **grid stability**. In addition, variable renewable energy sources have been covering almost all the power demand for an increasing period of time throughout the year. For instance, in 2020 the Eastern part of the Danish power system managed to run 13 percent of the time (a total of 1,181 hours) without any power generation from central thermal power plants, demonstrating that the system can be run safely without stability services being provided by central plants. The interconnectors and other grid components provided the required stability services.[36]

→ Denmark **overachieved** the **wind target** adopted in 2012,[37] which aimed to cover half of the power supply from wind by 2020.

→ The **share of variable energy integration** achieved in Denmark is by far the **highest in the EU**. The only other EU country that has crossed the 40 percent threshold is Luxembourg, and only four countries had a variable energy share above 30 percent in 2021: Lithuania, Spain, Ireland and Portugal (in descending order). On average, EU Member States reached a share of 19 percent in 2021.[38]

→ The successful Danish experience has received international attention and is an inspiration for other European countries, and beyond, seeking to accelerate their transition away from fossil fuels and towards variable renewable sources in power generation. The Danish Energy Agency has a dedicated arm for **Global Cooperation.**[39] While starting conditions with respect to the existing generation mix, available cross-border interconnections and market structures require a tailored policy mix in each country, most of the **basic levers** used in Denmark **can be applied in all Member States**.

Continuity, innovation, dialogue

→ **Market mechanisms** have been key to unlocking flexibility potential and thus ensuring the **cost-efficient integration of variable RES sources**. From the introduction of hourly spot market trading in the early 2000s to the beginning of cross-border intraday trading in 2018, price signals, including negative prices, provided incentives for the

36 Danish Energy Agency (2021).
37 Ea Energy Analyses (2015).

38 Ember (2022).
39 https://ens.dk/en/our-responsibilities/global-cooperation

operators of thermal plants to adapt generation outputs to system needs. Market mechanisms now also play a key role in **unlocking flexibility potential on the demand side**.

- Another key enabler has been **market integration across borders**, starting with interconnectors to Sweden and Norway and the creation of the integrated **Nord Pool** market, followed by **EU-wide** market integration. Making **interconnector capacity** available to market trading rather than determining its use through long-term contracts has allowed this capacity to be **used dynamically based on current system needs**. Market integration allows the matching of power supply and demand over a greater geographic area, and thus **lowers the cost** of integrating variable renewable energy.
- Danish **energy market players**, in particular the **grid operator** Energinet, are **continually innovating to further push the boundaries** of what is at first considered possible when integrating variable RES.
- Experience has shown that a **tailored institutional set-up** at the **local level** contributes to **accelerating the transition**. A **climate council** gathering all local stakeholders, with a secretariat as its executive arm, is recognised as playing an essential part in **developing a vision and defining action plans at the municipal level**. In coordination with other municipal departments, the municipality is then equipped to provide **a bottom-up assessment** and to **integrate local needs and concerns**, holding **consultations** with local stakeholders. Moving forward, the climate council could also help to assess and optimise further developments, such as replacing old turbines with larger and more efficient ones, installing new solar plants, developing power-to-X (heat, hydrogen), and expanding or reinforcing distribution grids.

From the 2020s, the increasing level of political ambition and **accelerating pace of transition** have required all players to agree on a different approach to conception and implementation. Specifically, Denmark has moved from an incremental, detailed planning roadmap to a **shared vision** for a 100 percent RES power system that is to be directly and fully implemented based on **selected and prioritised operational and organisational changes**.

GHG EMISSIONS REDUCTIONS & COSTS

Fast decarbonisation rate & low emission intensity of electricity generation

- Denmark has one of the **highest rates of decarbonisation in electricity production, 81 percent,** in Europe, over the period 1990-2021. Denmark has also a low GHG emissions intensity in electricity generation of **130g CO_{2e}**, compared to the EU average of 275 g CO_{2e} in 2021.[40]
- Between 1990 and 2020, **emissions** from the Danish **energy supply sector decreased** by **72 percent**. By comparison, the EU-27 achieved a reduction of 47 percent over the same period. In absolute terms, CO_2 emissions from energy supply were 19 Mt below 1990 levels in 2020.[41]
- Both **energy efficiency** improvements and **renewable energy expansion** have contributed to this success.

Renewable energy financing & power price levels

- Until 2021, investment in renewable energy plants was financed through the **Public Service Obligation** (PSO), a green surcharge on electricity prices. Together with other taxes it led to Denmark having the **second highest retail electricity price in the EU**

40 EEA (2022a).

41 EEA (2022b).

after Germany. In 2016 however, the government agreed to phase out the PSO and support renewable energy investment through the **public budget**, with the expectation this would **reduce retail power prices** by approximately **10 percent.**[42] The reform fulfilled a long-term demand from businesses for lower electricity prices. Since the **renewable energy expansion** has led to relatively **low average spot prices** for electricity, in 2018 the Danish government expected electricity prices for business to become among the lowest in Europe from 2022 onwards.[43] , Given the energy and security crisis, this expectation has yet to be fulfilled. Electricity prices for non-households in Denmark have not increased as much as for households in 2022 and remain within the EU average. [44]

→ Today **the cost of both solar farms and wind turbines has declined**, increasing the number of viable projects without state subsidies.[45]

42 Kapervicius and Balezentis (2022), p. 25.

43 Danish Ministry of Energy, Utilities and Climate (2018), p. 29.

44 Eurostat, 2023.

45 EnergyWatch (2022)

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