INTEGRATING HIGH SHARES OF VARIABLE RENEWABLE ENERGY INTO THE GRID: LESSONS FROM THE WORLD LEADER DENMARK IMPLEMENTATION MEASURES

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ACTION AREA: Mitigation

FOCUS AREA: Delivering

COUNTRY: Denmark

SECTORS INVOLVED: Energy (Electricity)

TIMEFRAME: Ongoing

CASE SUMMARY: Denmark is the global forerunner in the deployment of wind energy for electricity generation and one of the world's leaders in the deployment of renewable energies. Several factors have been crucial to ensure this leading position in the wind energy sector.

First, the Danish government adopted ambitious and legally binding renewable energy targets, energy support schemes and detailed technical regulations to promote and faciliate the deployment of wind energy. Second, the county introduced a number of flexibility mechanisms for conventional power plants to adjust to the entry of wind energy into the power market. Third, Denmark liberalized its power market allowing smaller firms and renewable energy producers to enter the market. Fourth, Denmark decided to join a cross-country power market with other Scandinavian countries and Germany to sell excess wind power at times of strong winds and buy electricity at times when wind production is low. Fifth, the country set up an advanced wind forecasting system to get real-time estimates on how much wind energy can be fed into the grid.

The way in which Denmark has managed to integrate increasing shares of wind energy into the grid has been characterised by strong political commitment, long-term planning and a high level of transparency. The country is an example for other countries with regard to how to create a well-functioning electricity market that is able to cushion the variable character of wind energy. From the 1970s until today, Denmark is a pioneer and global leader in the system integration of variable renewable energy and it has the highest share of wind energy for electricity generation worldwide. And Denmark is committed to retain its leading position: it pursues world-leading targets for the decades to come (inter alia to meet at least 50 % of energy demand with renewable energy by 2030 and complete independence from fossil fuels by 2050) and is convincingly on track to meet the latter through its ambitious policies (IEA, 2017b).

BACKGROUND:

The oil crisis of 1973 stimulated a radical transformation of the Danish energy system. Previously based on centralized and conventional energy, Denmark drew its lessons and actively pushed for an energy diversification agenda, encouraging the development of decentralized and renewable energy. Due to its geographic location Denmark has some of the best wind conditions in the world. This has paved the way for the country´s unique position as a global pioneer in the use of wind energy for energy and electricity generation and as one of the world leaders in wind energy technology. This is shown by its early leadership in wind energy deployment, triggered by the conviction of national leaders that dependency on oil and gas needed to be overcome in the long run. Subsequent measures taken in the following decades secured this historical leadership role, inter alia through the conclusion of ambitious political agreements underpinned by binding targets.

The country´s first energy plan of 1976 heavily focused on the development of the wind energy sector (Ea Energy Analyses et al., 2017). This was followed by the first taxes on electricity prices to finance research and development (R&D) on renewable energy in the 1970s as well as subsidies for investments in wind turbines in the 1980s. In the 1990s, Denmark introduced a feed-in tariff for wind electricity generation (IRENA-GWEC, 2012). It also liberalized its power market and opened up for commercial activity to grant firms that produce renewable energy equal access to the market (Ea Energy Analyses et al, 2017). Taking the aforementioned measures, Denmark has pioneered new policy approaches regarding the grid integration of renewable energies that in many cases have become common good practice internationally.

At the beginning of 2000, Denmark unbundled energy production from transmission. Transmission was turned into a state-owned task, leading to the establishment of the state-owned transmission system operator (TSO) Energinet (Agora Energiewende, 2015). It supports the stability of the grid (Danish Energy Agency, 2015a) and secures fair access to the grid for all market participants. In 2001, Denmark together with other countries established the Nord Pool Power Exchange Market. The purpose was to link the Nordic power markets and enable transnational electricity trading. The common market was another stepping stone for the further integration of wind energy as it allowed to sell and buy energy according to demand within a larger area. The interconnectors to neighboring countries have helped Denmark to integrate high shares of wind power into its power system and allow balancing out fluctuations in wind energy production and energy consumption patterns, thus maintaining stability. Over the last years, the TSO Energinet has developed detailed technical regulations and protocols for the management of the power system to keep it reliable and balanced.

In 2008, Denmark established the Danish Commission on Climate Change Policy to investigate how Denmark could become independent from fossil fuels in the future (Ea Energy Analyses et al, 2017). 2009 saw the establishment of a policy support mechanism based on price premiums added to the market price, and tenders for offshore wind power (IRENA-GWEC, 2012). These subsidies' costs were passed on to consumers as an equal Public Service Obligation tariff on their total electricity consumption (ibid). In the future, these costs will be covered by the Danish government budget due to competitiveness concerns for Danish businesses (Weston, 2016). In the following years, two other agreements were set up that ensure Denmark´s transition towards a renewable energy-friendly nation: the Danish Energy Strategy 2050 (Danish Energy Agency, 2015a) and the Danish Energy Agreement for 2012-2020 (International Energy Agency, 2017a) which sets legally binding targets for the expansion of wind energy for the period up to 2020. In June 2018, the Danish government signed a new agreement that reaffirms and strengthens the country's ambitious goals to expand the construction and use of renewable energy (State of Green, 2018a).

Evidently, the Danish efforts for wind energy integration into the grid and an increase in the percentage of variable renewable energy in total energy generation are paying off. Preliminary numbers show that renewable energy's share of energy consumption rose again in 2017. The share of renewable energy in adjusted gross energy consumption increased from having covered 29.1% in 2016 to covering 32.3% in 2017 (Danish Energy Agency, 2018). Wind turbines supplied enough power to cover 43.4% of Denmark's electricity consumption in 2017 - the highest share ever recorded (State of Green, 2018b).

By 2022, Denmark is expected to generate about 70 % of its electricity through variable renewable energy, with the vast majority being generated by wind energy. The graphic below published by the International Energy Agency (IEA) depicts Denmark´s continued world-leading position in that regard. On another note, the World Bank seconds Denmark´s global leadership role in the support of renewable energy: a recently published report hails the country for having the strongest regulatory and legal framework for renewable energy worldwide (Banerjee et al., 2017, p. 135).

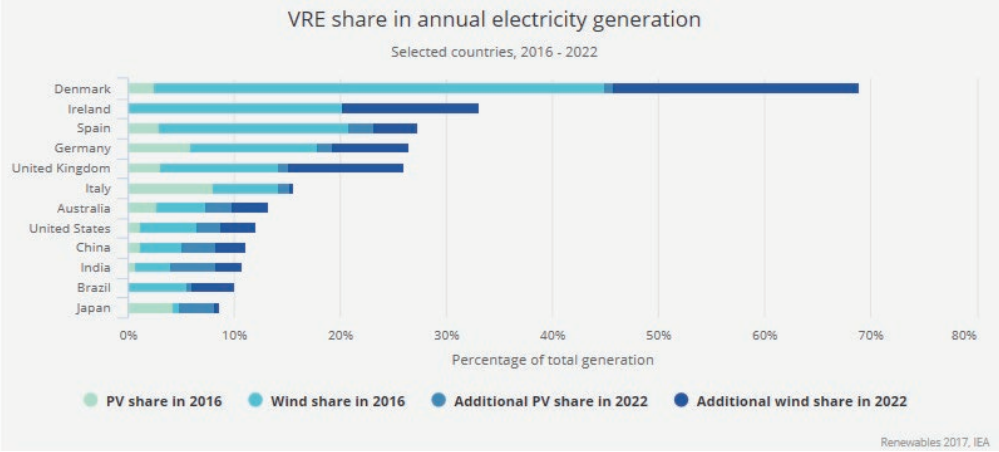

Figure 1: Share of variable renewable energy in annual electricity generation for the years 2016-2022 in selected countries (IEA, 2017d)

ACTIVITIES:

- **SETTING UP LONG-TERM GOALS FOR THE DEPLOYMENT OF WIND ENERGY:** The Danish government has set out binding and ambitious climate policies through the Danish Energy Agreement for 2012-2020. According to the Agreement half of the electricity consumption will have to come from wind power by 2020, which will enable a share of 35% renewable energy in gross energy consumption by that time (International Energy Agency, 2017a). In order to achieve these targets, the agreement makes provisions for a substantial expansion of wind power (for example by building 600 MW offshore wind turbines at Kriegers Flak and 400 MW offshore wind turbines at Horns Rev before 2020) and commits a total of DKK 100 million (approx. EUR 13.4 million; USD 15.6 million) to funding development and use of new renewable energy technologies for electricity production (International Energy Agency, 2017a). June 2018 saw the signing of a new government agreement that includes inter alia the establishment of three new offshore wind farms with a total of 2400 MW and the allocation of DKK 4.2 billion (approx. EUR 564 million; USD 649 million) to a tender process through which different technologies such as onshore wind turbines and solar cells compete for delivering green electricity at the cheapest price (State of Green, 2018). The Danish government has also established plans to require at least 50 % of its energy to come from renewable energy sources by the year 2030 (Gyekye, 2018). Additionally, the Danish Energy Strategy 2050 aims

to achieve 100% independence from fossil fuels in the energy mix and 100% of electricity from renewables with a focus on wind energy by 2050 (ibid). The scope of these goals makes Denmark a role model also for other states that are already taking ambitious measures to expand the use of wind and other renewable energy in the energy mix.

- **FLEXIBILIZATION OF THE POWER SYSTEM:** Denmark adopted a number of technical and operative requirements to enable balancing out variability in renewable energy production. These "flexibility measures" include the use of "must-run units" to secure system stability, rapid response rates, lower minimum output, and short start-up times (International Energy Agency, 2017b). Such measures ensure that conventionally-fired plants (using coal, biofuels, waste and natural gas) do not have to run at all times but are prepared to step in when there is not sufficient wind energy available to satisfy existing demand.

- **LIBERALISATION OF THE POWER MARKET:** In the late 1990s Denmark liberalized its power market to stimulate the entry of new market participants, allow consumer choice, induce competition and drive down prices on renewable energy. The liberalisation process also entailed the corporate un-bundling of energy generation and energy transmission and the establishment of the state-owned Transmission System Operator Energinet in 2004. The reason behind setting up a public entity was to ensure efficient operation of the national electricity infrastructure as well as ensuring equal access for all energy producers.

- **PROVISION OF TECHNICAL REGULATIONS FOR IMPROVED INTEGRATION OF WIND ENERGY:** Denmark introduced detailed technical regulations (such as grid codes that define the requirements to generation) for the integration of wind energy into the grid. These regulations help to ensure the physical operation of interconnected high voltage grids and security of supply. They also help to integrate other renewable energy sources into the grid by providing guidance on the technical requirements they should fulfil (Danish Energy Agency, 2015a).

- **MARKET BASED POWER EXCHANGE WITH NEIGHBOURING COUNTRIES:** Denmark together with Sweden, Norway and Germany, created the international power exchange market Nord Pool. Nord Pool allows Denmark to sell electricity to its neighbouring countries at times of excess wind energy production, and buy power abroad at times of low wind. The common market with Norway, Sweden and Germany has proved to be a successful way of interconnecting national energy markets through transmission networks (Agora Energiewende, 2015).

- **DEVELOPMENT OF A WIND ENERGY PRODUCTION FORECASTING SYSTEM:** The public operator Energinet has developed advanced wind forecasting systems that allow for real-time monitoring of the grid and create real-time estimates of wind power that are fed into it. This has been a key prerequisite for feeding-in high shares of wind energy into the grid while balancing supply and demand (Danish Energy Agency, 2015a).

INSTITUTIONS INVOLVED: Danish Ministry of Energy, Utility and Climate, Danish Energy Agency, Danish Energy Regulatory Agency, Energinet (Transmission System Operator), grid companies, Nord Pool.

FINANCE: The expansion of renewable energy has primarily been financed via the Public Service Obligation (PSO), which is charged over the electricity bill. This funding model will gradually be phased out from 2017-2022 in order to strengthen the competitiveness of Danish industry, giving the Danes a cheaper electricity bill (Weston, 2016). Beyond 2022, support for renewable energy projects is going to be financed from the Danish government´s budget (ibid).

IMPACT OF ACTIVITIES:

- **CONSIDERABLE INCREASE OF THE SHARE OF RENEWABLE ENERGIES IN OVERALL ELECTRICITY PRODUCTION:** Denmark's policies and measures in the energy sector have proved to be highly successful in enabling the integration of wind energy into the grid. In 2014, Denmark managed to increase the share of wind energy in the overall electricity generation to 39% (Agora Energiewende, 2015), the world's highest at that time. In 2015, the combined output of wind and solar PV equaled 51% in power generation (International Energy Agency, 2017c).

- **SUBSTANTIAL DECREASE IN CO2 EMISSIONS:** The changes in the energy mix have led to a remarkable decrease of 60% in CO2 emissions from electricity production in the period 1990 – 2015 (Danish Energy Agency, 2015b). Moreover, important conditions have been created to become independent from fossil fuels by 2050 which would lead to a further reduction in CO2 emissions.

- **CO-BENEFITS:** The strong incentives for wind power technology development spurred collaborations between research institutions and technology companies and supported Denmark's wind turbine manufacturers to become market leaders. This supported national industrial development and created new jobs.

WHY IS IT GOOD PRACTICE:

To enable the integration of high shares of wind energy into the grid, Denmark took political, economic and technical measures that prepare the ground for the successful materialisation of the government´s goals:

- **POLITICAL BUY-IN:** Through the long-term vision formulated in the Danish Energy Strategy 2050 as well as the formal and legally binding renewable energy targets for the years 2012-2020, Danish policy-makers show their willingness to transform the country into a low-carbon economy. These long-term goals and targets are generally developed by the central government with input by experts from academia, industry and consultants (Ea Energy Analyses et al., 2017), which enhances the inclusive character of the policies.

- **TRANSPARENCY:** The long-term goals of the Danish government regarding renewable energy were made transparent and measurable through concrete targets and policy measures, such as those included in the Danish Energy Agreement 2012-2020.

- **INNOVATION:** Denmark introduced a number of flexibility mechanisms and an advanced wind forecast system to address the challenges linked to variable renewable energy production. The flexibility mechanisms ensure that Denmark can respond flexibly to varying wind conditions in real time, for example by decreasing output from thermal power plants when the market signals an excess of wind power, thereby allowing for more efficient real-time dispatch of power plants (International Energy Agency, 2017b, p. 155).

SUCCESS FACTORS:

A number of factors were critical to create an environment conducive for the effective, stable and reliable integration of variable renewable energy including wind power – stretching from incentive creation through political frameworkds to building adequate market conditions:

- **AMBITIOUS, LONG-TERM AND STABLE POLITICAL FRAMEWORKS:** Ambitious targets, long-term planning and stable political framework conditions paved the way for a positive investment climate (Danish Energy Agency, 2015a). The Danish government has set up goals that exemplify its commitment to renewable energy deployment: 100% renewable energy in 2050, 100% renewable energy for electricity and heat in 2035 and the coverage of 50% of electricity generation by wind turbines in 2020 (stoRE, 2013).

- **A WELL-FUNCTIONING ELECTRICITY MARKET:** The Nordic power exchange Nord Pool ensures a cost-efficient cross-border transfer of power from areas with high production and low demand to areas with low production and high demand. This provides power producers with a clear incentive to adapt production to market signals (Danish Energy Agency, 2015a).

- **STRONG AND INDEPENDENT TSOS:** Transmission System Operators are vital for a successful system integration of wind power. Over the years, Energinet, the Danish TSO, has efficiently cooperated with neighboring TSOs, created robust interconnections with these countries and managed to ensure almost perfect grid stability (Danish Energy Agency, 2015a).

OVERCOMING BARRIERS / CHALLENGES:

WHAT WERE THE MAIN BARRIERS / CHALLENGES TO DELIVERY?	HOW WERE THESE BARRIERS / CHALLENGES OVERCOME?
INFORMATION: The intermittent nature of wind production patterns constitutes an obstacle to the provision of stable power supply by the responsible Danish institutions.	The need to confront the unpredictability of wind energy and increase the ability to integrate and balance high shares of renewable energy has been identified. To that end, Denmark has incorporated advanced wind forecasting in the operations of power system control and dispatch through the Danish Transmission System Operator Energinet (Danish Energy Agency, 2015b).
ECONOMIC: The economic value of wind energy decreases with increasing shares of wind energy in the grid.	Due to the fact that wind turbines can produce electricity at very low variable cost, they drive more expensive power plants out of the market when production is high and lower the electricity price. This not only constitutes a burden for conventional power, but is also detrimental to the revenue of wind turbine operators. Ultimately, it can be a disincentive to investments in new wind turbines. A remedy for the decreasing socio-economic value of wind energy at times of high power feed-in is the use of flexibility options. These include exporting wind power to other countries, reducing power production of conventional plants and increasing consumption at times when it is economically attractive (Agora Energiewende, 2015).

LESSONS LEARNED:

- **INTRODUCE SUPPORT SCHEMES TO MAKE INVESTMENTS IN RENEWABLE ENERGY ATTRACTIVE:** The fixed costs of investing in renewable energy were initially higher compared to conventional energy sources such as coal. This can be an obstacle to initial investments in low-carbon technologies. To create a positive investment climate and increase the competitiveness of renewable energy, Denmark introduced support schemes such as subsidies for the construction and operation of wind turbines and taxes on conventional energy (Danish Energy Agency, 2015b). This led to lower levelized cost of wind energy.

- **MAKE THE POWER SYSTEM MORE FLEXIBLE AND ADAPTABLE TO THE INTEGRATION OF VARIABLE WIND ENERGY:** To confront the challenges that arise from the integration of fluctuating energy sources such as wind, Denmark introduced measures that increased load flexibility, e.g. by reducing minimum load of conventional power plants that normally ensure system stability. Also, ramp up rates were reduced, e.g. for coal fired plants (Agora Energiewende, 2015).

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HOW TO REPLICATE THIS PRACTICE:

- **SECURE POLITICAL COMMITMENT:** Denmark's transition to a low-carbon economy is fostered by clear and ambitious goals and long-term planning. . This is crucial in order to signal a clear pathway to businesses and to the wider public. Seek political commitment from the very beginning. Demonstrate the benefits of a low-carbon economy for citizens and businesses, involve relevant political and interest groups, and develop an ambitious and long-term strategy and action plan.

- **PROVIDE CLEAR TECHNICAL REGULATIONS:** The detailed technical specifications ensure flexible electricity supply and high power stability. For example, the Danish grid codes specify properties that power plants must possess throughout their technical service lifetimes in order to be connected to the Danish public electricity supply grid.

- **MAKE USE OF MODERN TECHNOLOGY AND OPERATIONAL PLANNING TOOLS:** To address fluctuations in wind energy production patterns, set up a forecasting system and develop clear procedures and protocols for the control centre. A modern wind forecasting system supported by operational planning tools (e.g. protocols) can help the TSOs in the running of the wider power system including possible activation of regulating power generators.

- **SPUR COOPERATION WITH NEIGHBORING COUNTRIES:** Through the interconnection with a wider grid area, the intermittency in the national generation profile of variable renewable energy can be smoothened out. Power supply can be secured and overcapacity can be sold.

- **UNBUNDLE GENERATION AND TRANSMISSION:** This ensures that transmission companies do not have commercial interests in the production side. It also ensures equal access for all users of the electricity infrastructure (Danish Energy Agency, 2015a).

CONTACT FOR ENQUIRIES:

Henrik Breum, Special Advisor,
Danish Energy Agency, Centre for Global Cooperation
hebr@ens.dk

Peter Jørgensen, Vice President (Associated Activities)
Energinet
PEJ@energinet.dk

FURTHER KEY RESOURCES: The Danish Government (2011). Energy Strategy 2050. Summary. Available at: http://dfcgreenfellows.net/Documents/EnergyStrategy2050_Summary.pdf

WEBSITE: Danish Energy Agency about Wind Power: https://ens.dk/en/our-responsibilities/wind-power

CASE STUDY AUTHORS: Helen Burmeister, Tobias Hausotter and Nikolas Scherer (adelphi)

CASE STUDY CONTRIBUTORS: Interviewees: Henrik Breum and Peter Jørgensen (see contact for enquiries)

EDITED BY: Marie-Jeanne Kurdziel (New Climate Institute)

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REGISTERED OFFICES:
Bonn and Eschborn

Dag-Hammarskjöld-Weg 1-5
65760 Eschborn, Germany
+49 6196 79-3330
klaus.wenzel@giz.de

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