Danish Experience

- How to reach > 40% Wind Energy Share -

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***Abstract*—The use of wind energy is a story of success in Denmark since its start in the 1970, characterized by continuous development of various components of the energy system and rules around it. This paper gives a short overview of how it was possible to reach the current energy share of about 40% of electricity consumption.**

Keywords- Denmark; wind energy; energy system

I. Introduction

When the first modern wind turbine was erected in Gedser, Denmark in 1957, nobody had the idea that this technology, some development-stages later, will one day provide a significant share of the Danish electricity consumption. Other countries followed integrating and further developing this technology, and today the use of wind and other renewable energy sources is even at the top of the European energy agenda. Climate targets for 2050 and 2030 are set, following the first binding EU-wide RES targets for the year 2020 which had been defined in 2009 [1], specifying targets for each European country.

For 2020, Denmark aims at a 30% RES share of its total energy consumption, i.e. referring to heat and electricity, which is estimated to trigger a 50% electricity demand coverage by wind energy. In 2016 (2015), a 37,6% (42%) energy share was reached, which is already quite close.

The development over decades (Fig. 1) shows a constant growth of RES usage including usage of offshore wind since the early 1990s. Danish political energy targets aim at not using any fossil fuels by 2050. Key figures describing the current power system can be found in table 1. A comparison of high-RES countries is provided in [3].

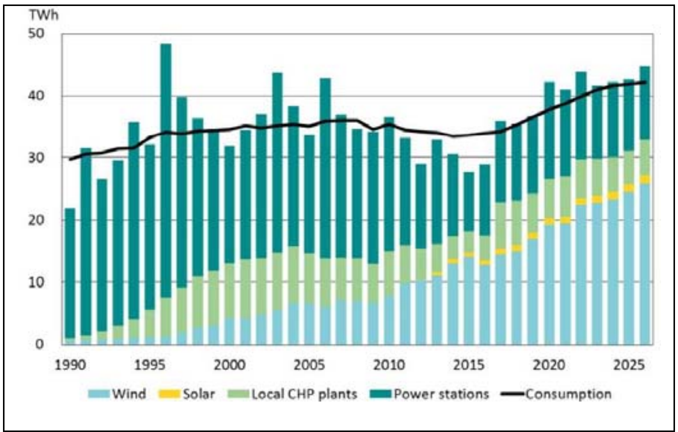

Figure 1. Electricity Consumption and Generation in Denmark [2]

Main facilitating factors for this development are a combination of different measures and the exploitation of geographic conditions.

I. Key Factors – The Energy System's Tool Box

While the wind industry over the years has minimized the investment costs for new turbines, the value of wind power for society was maximized by other market participants. In general, a flexible system is needed where i) the cheapest energy is used first, ii) energy spillage is avoided, iii) the full technical potential of RES technology is used and iv) investment conditions for all market participants are attractive.

TABLE I. The Danish Energy system - Key Figures [2]

Development in RES		
	2015	***2016***
	GWh	***GWh***
Net electricity generation	27,704	28,930
Net Import	5,912	5,057
Consumption (incl grid losses)	33,616	33,987
Breakdown of electricity generation	***GWh***	***GWh***
Wind, solar and hydro electric power	14,133 605 19	12,782 744 19
Electricity from thermal Generation based on biofuels	3,789	4,266
Electricity from thermal Generation based on non RE fuels	9,159	11,119
Share of RES	***%***	***%***
Wind power share of net generation	51,0	44,2
Wind power share of consumption	42,0	37,6
RE share of net generation	66,9	61,6
RE share of consumption	55,2	52,4

Analyzing the last 30 years of Danish energy system development, some key factors supporting these needs can be identified. They can be divided into technological conditions, proper international and national energy market design and stable economic framework conditions.

A. Technological conditions

1) Strong transmission grid and interconnectors

As Denmark is located between a mainly thermal system in the South and a hydro-based system in the North, the geographic advantage has been exploited by building strong connections to both neighboring systems. Additionally, both Danish energy systems belong to different synchronous areas (Fig.2), thus connections to the neighbors use either AC or HVDC technology, depending on the system to connect to. In this context, HVDC technology is beneficial, as flows can be controlled while AC technology is beneficial, as it increases the electric system. Both was needed when adding wind power mainly to the small western Danish system.

The Nordic hydro-based system follows seasonal patterns and is excellent to balance the variability of wind power. In contrast, the strong continental thermal-based system supports frequency stability, thus respective AC connections have been reinforced over the past decade and this process still goes on as long as the benefit for society is higher than the costs.

The Danish systems are very well connected: strong interconnections can import 95% of the peak demand or export 59% of installed production capacity. Surplus wind energy can be exported and security of supply is ensured when the wind is not blowing.

Anyway, new challenges start to materialize, as not only the Danish energy systems since the 1980s, but also neighboring systems since the 1990s change: large-scale integration of RES supplements the overall plant fleet with low OPEX- energy and pushes thermal plants out of the market. This impacts the provision of ancillary services, as classical thermal power plants begin to close down. As a consequence, variable renewables have to provide system support as well, e.g. inertia, short circuit power, support of black start capability, voltage control, dynamic voltage support etc.

Another challenge is that the internal electricity infrastructure in many European countries needs upgrades to facilitate long-distance RES transport, exploiting lower correlation of weather conditions. In general, cross border interconnections are triggered by wholesale electricity price differences on both sides of a border. As the fleets change, also price structures change. Between 2008 and 2016, the neighboring German and Swedish systems e.g. faced wholesale prices decreases of 59% and 57% respectively. An ex-post analysis [4] investigated this drop and found for the thermal-based German system, that RES integration caused the main drop, while the opposite effect was triggered by the German nuclear phase out. Coal and gas fuel prices declined, the European ETS CO2 collapsed and some further moderate decrease was caused by investments in power plants and decreased demand. The latter drop was compensated by international trade. Similar investigations for the mainly hydro based Swedish system concluded [4]

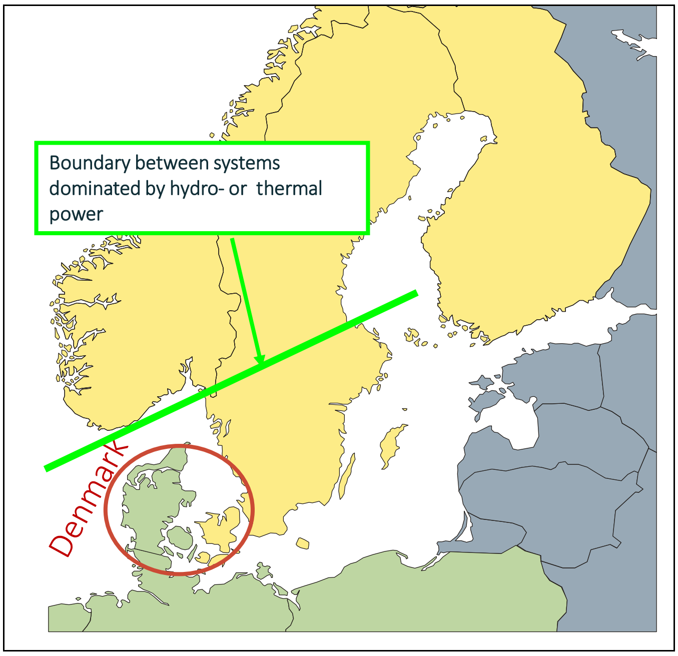

Figure 2. Three synchronous systems around Denmark

that the drop was caused by different effects: while RES integration, high hydro inflow and less demand caused significant decrease of about 80% of the wholesale price, net exports compensated the main share of this development again.

For European TSOs, grid planning is becoming more challenging, as investments in infrastructure have to be robust for a broad spectrum of potential developments. International TSO collaboration in ENTSO-E helps to identify the right investments.

2) Flexible energy system

The higher the share of variable RES in a system, the more focus is put on system flexibility.

One characteristic feature of the Danish energy system is the close coupling of the electricity and the heating sectors. Both, the big power plants and the hundreds of small CHP units feed into both systems and supply a high share of consumers who are connected to district heating. The CHP units have relatively big heat tanks, thus they are able to decouple heat and electricity production to a certain degree, which is important during times of high wind. As a next step increased use of heat pumps is envisaged.

Another effect is reached by extending power plants' limits: While classic thermal power plants usually are operated in a range between 35% and 100% of their rated power, Danish plants are developed to cover a range down to 10% of their rated power. In this way they can stay in operation helping to balance the system while expensive start-up costs are avoided.

Fast regulation is also key in a system with variable resources and consumption. Modern plants are able to act with a regulation rate of 3-4% per minute.

For Denmark, future flexibility needs have been analysed, evaluating the residual load (load minus wind-minus solar power) for different time periods. For this purpose 10 years' time series for Denmark and neighboring countries of production and demand have been used. Results show that flexible demand and vehicle-to-grid provide useful services for periods shorter than 5 hrs, but periods of longer than 12 hrs need other means, e.g. exchange with neighbors and market means [5]. Flexibility needs to get a price reflecting the needs, which might change the accounting system [6].

3) *High quality forecasts*

Historically, the production fleet was controlled and only the consumers' behavior had to be forecasted. A RES-based system needs more focus on forecasts – both, for consumption and for variable RES production. Considering e.g. the wind along the western Danish coast, a small change in wind speed of e.g. 1 m/s triggers a difference of 500 MW electricity production – this is the size of a classical thermal plant block. This difference has to be balanced by other plants or interconnections. If this change in wind speed can be forecasted within 15 min or faster, automatic reserve is activated. This reserve is based on contracts with producers.

System balancing during the last hour before operation is covered by the Danish TSO, using a couple of forecast tools and operational plans provided by producers. Energinet.dk's control center estimates the unbalance between production and consumption. Consumption-forecasts were improved significantly over the past decades – now considering higher amount of historical data and temperature-correction, as consumption is increasingly sensitive to the weather.

Wind forecasts are conducted combining model data (numerical weather prediction - NWP) and online measurements close to the operational hour. For the NWP the country is split into 25 wind areas, where the wind output is calculated evaluating wind speed and the power curves of the turbines being installed at these locations This is calibrated using historical wind data and considering the expected electricity price in that area. Very close to the operational hour important improvements are made by adding information from online measurements, which are installed at about one third of Danish wind turbines and are updated every 5 minutes.

Unbalances within the operational hour are mitigated using a list of currently available power plants from all Nordic countries, delivered to the list by balance responsible parties. Activating bids from this list is slower but cheaper compared to using automatic reserve [7].

B. *International Electricity Markets*

The European liberalization of the energy market in the 1990s required significant changes of the up-to-then vertically integrated energy supply companies. Generation, transmission and trade were separated, new companies were founded and new roles and responsibilities were allocated. The basic idea was that always the most efficient electricity producer should deliver energy to the consumer via balance responsible parties.

In this context, new markets for several time horizons had been developed reaching from several years ahead down to minutes ahead. For variable renewable resources, especially the short-term markets are important, as they facilitate efficient integration of variable units into the energy system. Here the 1-hr-ahead spot market and balance markets with even lower time resolution have proven to be efficient over the last decades, as they provide flexibility.

Market design has continuously been further developed, evaluating the lessons learned and optimizing details of the rules. Negative prices have been implemented and one of the latest activities was the "markets model 2.0" project coordinated by the Danish TSO [8]. All market participants jointly developed ideas to further incentivize increase of flexibility in the system, both, originating from the production and the consumption side as well. An analysis of needs to cover critical services followed, part of it potentially being solved by the implementation of new network codes currently being developed at European level. Today, even wind power plants react on market signals.

An overview of market designs for high level of variable generation is provided in [9] comparing US and EU solutions and trends. The paper concludes, that market evolution is complex and that energy only markets are in many cases replaced by a combination of energy, ancillary service and capacity markets, with non-trivial interactions.

C. *Stable economic conditions*

When introducing significant changes to a system, it is important for investors that they can trust in stable political and financial framework conditions. Long-term political targets with a broad acceptance across most political parties and the administration's support of the development of necessary tools, be it technical or market rules, reduces investor's risk, and thus accelerates the desired development.

An example is the current development of network codes at European level, comprising the three areas connection, operation and market – not only considering RES.

II. Future Development

The targets of the European Energy Unions focus on security of supply, the realization of the internal energy market and energy efficiency, which means increased regional collaboration between European countries and energy companies.

Climate targets beyond the above mentioned 2020 targets aim for Europe at a CO2 reduction of 80-90% related to 1990, implying that Denmark will contribute with a reduction of 40% related to 1990 level. This target requires detailed analysis and contribution of all stakeholders and sectors. The energy transition of other sectors e.g. also the transport sector triggering a higher degree of electrification affects infrastructure needs for electricity and gas as well. Coupling between sectors needs to be intensified. Respective investigations are published in [5], Fig.3 showing the general principle.

The past decades' efficient integration of a high share of wind energy was possible due to the continuous development of market mechanisms, technical improvements, new operational methods and -tools and the expansion of international infrastructure. Further RES integration will additionally require new methods and mechanisms and intense regional collaboration.

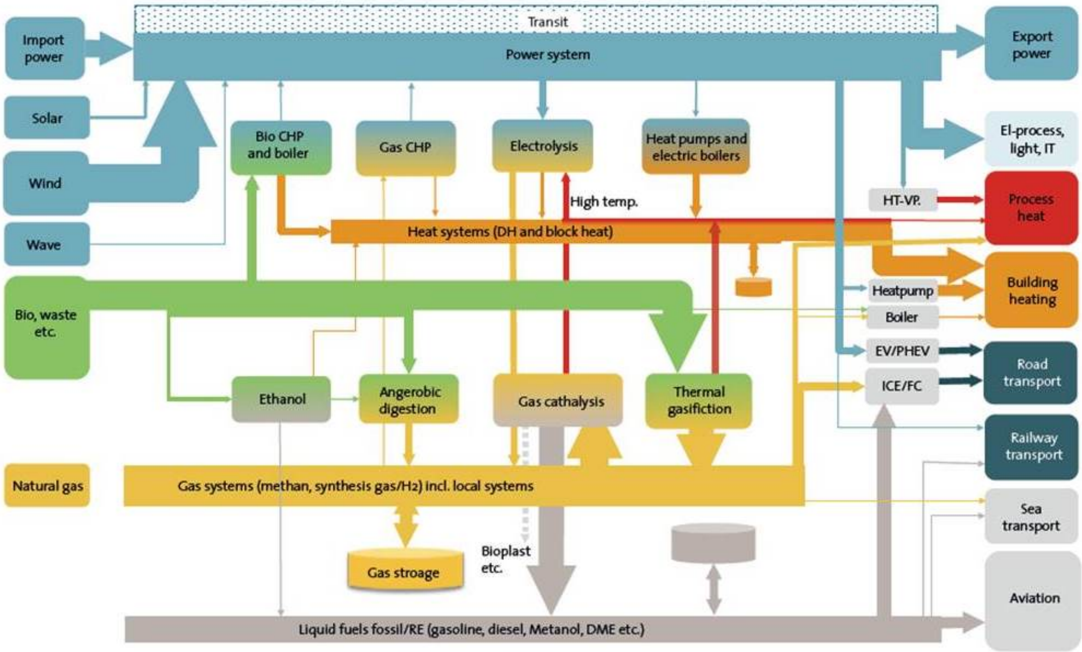

Figure 3. Potential sector coupling 2050 [5]

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BIOGRAPHICAL INFORMATION

Antje Orths has graduated in electrical engineering from the Technical University of Berlin, Germany and received her Ph.D. from the OvG.-University Magdeburg, Germany, where she is adjunct professor beside her main job in Denmark.

She works since 12 years as chief engineer for the Danish TSO Energinet.dk in Fredericia, Denmark. Currently she works in the Electricity System Development Unit with responsibilities in international infrastructure development in both European associations ENTSO-E and ENTSOG. She is convenor of ENTSO-E's Regional Group Northern Seas and represents Denmark in an IEA Task force.

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