Powering Indonesia by Wind

Integration of Wind Energy in Power Systems

A Summary of Danish Experiences prepared for Indonesia

Final report, January 2017

An Innovative Partnership for the 21st Century

MARITIME | URBAN & CLEANTECH | AGRI-BUSINESS | DESIGN & LIFESTYLE | HEALTH & LIFE SCIENCES

Content

1 Introduction

The aim of this report is to describe Danish experiences with wind integration and discuss their relevance regarding the integration of wind and solar power in Indonesia, particularly regarding grid connection. In this respect, Indonesia is facing the following tasks and challenges:

1) To establish policies and regulatory measures that will help accelerate the development of wind power and other variable renewable sources.
2) To ensure a secure and stable electricity system where demand and supply is balanced, system operation is smooth, and voltage/frequency is under control, even if 10% or more of the energy mix is covered by wind power production in the future.
3) To ensure an economically efficient operation of the electricity system with an optimal utilisation of wind power.
4) To evaluate potential wind power projects and on the basis of evaluations, to decide which potential wind power projects can be approved and accepted for grid connection, while still maintaining a secure and balanced electricity system.
5) To ensure a smooth integration of solar power in the Indonesian power system.

The specific focus of the report is thereby on regulatory and technical power system integration challenges, primarily related to wind power. The report is based on Danish experiences with integration of wind power, and these experiences are - to the extent possible for the Danish experts with their current knowledge of the Indonesian electricity system - related to the Indonesian context. Chapter 2 provides an historical overview of wind power development in Denmark. Chapter 3 focuses on the nature of power generation from wind turbines; chapter 4 discusses how policy can support an expansion of wind power, and chapter 5 shares Danish experiences from operating the power system with high wind power penetrations of up to 42%. Chapter 7 discusses Danish experiences with power system flexibility measures designed to aid the integration of wind power and chapter 9 discusses how to assess and approve grid connection of wind power plants. Finally, chapter 10 will briefly discuss Danish experiences from grid integration of photovoltaics. Based on lessons learned from Denmark, the end of most chapters will discuss how to address challenges faced by Indonesia today with regards to the topics of the specific chapters.

This specific composition of topics is the result of discussions between the Indonesian and Danish partners in the project.

The report will provide additional information, knowledge and guidance to MEMR (e.g. DG Electricity and EBTKE) and PLN as well as other stakeholders involved with the regulatory and technical aspects of integrating wind and solar power into the power system in Indonesia. The report is equally intended to form the basis for a fruitful discussion between Indonesian and Danish experts.

2 Historical development of wind power in Denmark

This chapter will describe wind power development in Denmark from the very first initiatives taken by pioneers, through the energy crisis in the 1970s, and the beginning of the modern wind industry up to the most recent developments of the wind industry looking into onshore and offshore wind power in Denmark today. The chapter will also describe the electrical power system in Denmark today, and through the historical overview, external factors that led to growth in the wind industry, particularly changes to the Danish power system, will be discussed.

2.1 The oil crisis in the 1970s and the foundation of the modern wind industry

The Danish physicist Poul la Cour built the first electricity generating wind turbine in 1891 with funds from the Danish government. The wind turbine produced direct current, and supplied its electricity to the school where Poul la Cour was a teacher, and later also to some of the villagers in the small town Askov in Denmark.

Danish engineers improved the wind turbine technology during World War I (1914-18) and World War II (1939-1945) in order to maintain the electricity supply during energy shortages. By the end of World War I, 3% of Danish electricity consumption was covered by wind power.

At the start of World War II, the Danish company, F.L Smidth, developed a new wind turbine with aerodynamic wings. The Smidth turbines are considered frontrunners for the modern wind turbine generators. After World War II, another pioneer of the Danish wind industry, Johannes Juul, further improved the wind technology and developed the famous Gedser wind turbine. The 200 kW Gedser wind turbine generated 2.2 million kWh in 1956 -67. Despite Johannes Juul's success with the Gedser-turbine, the Danish Association of power stations, whom had contributed with funding of the Gedser wind turbine, decided to suspend the wind power programme in 1962 with the justification that due to the current low oil prices wind turbines would not be able to compete with traditional power plants.

However, the energy crisis in 1973-74 changed this perception. In 1973, oil prices increased significantly, and as a result, wind energy as well as other alternative energy sources regained interest. The interest in alternative energy technologies was now represented in both the general population and amongst the politicians in Denmark.

Following the oil crisis, one of the first modern wind turbines, the "Tvind-turbine" was built, driven solely by public initiatives. A key driver behind the Tvind-turbine was a resistance towards nuclear power. Denmark at the time of the oil crisis did not yet have any nuclear power stations, however plans for construction of Denmark's first nuclear power plant were well advanced, and the Tvind-turbine was a hope for an alternative energy solution to nuclear power. The Tvind-turbine was erected in 1975-78, and became an important source of inspiration to the key technicians in the upcoming wind industry.

The energy crisis in 1973-74 also made politicians aware of the necessity of long-term planning and regulation of the energy sector. The first Danish energy plan dates back to 1976, followed by the introduction of an electricity supply act, a heat supply act, and an act regarding the introduction of natural gas in 1979. The development of renewable energy technologies also became a high priority among politicians. In 1978, a test station for wind turbines was established at Risø near Roskilde in Eastern Denmark, and the year after, the parliament agreed to subsidise to 30% of the total project costs for new wind power projects. This subsidy system was in place until 1989, when it was changed to a feed-in tariff. Chapter 4 further discuss the political initiatives to support wind energy in Denmark.

Since the first energy plan in 1976, various governments throughout the years released several reports presenting comprehensive plans of the Danish energy sector development.

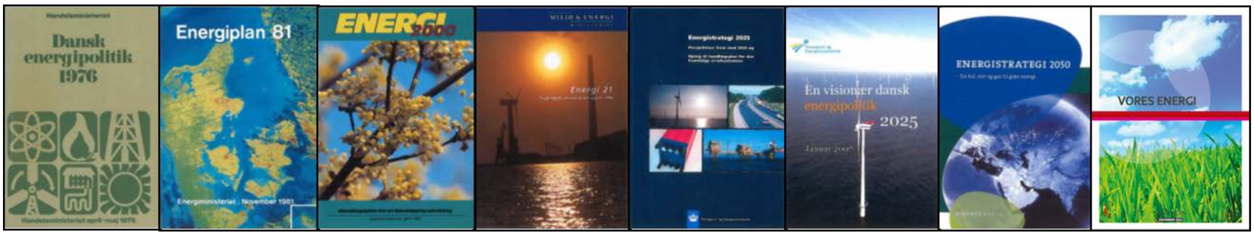

Figure 2-1: Energy plans in Denmark

In the second energy plan released in 1981, nuclear power was still included, however, with the precautions of conducting further investigations into the handling of nuclear waste and general security issues. The energy plan likewise mentioned that based on the nuclear investigations, if the government were to decide to apply nuclear power, the decision would first have to go through parliament and if passed, the question would be put to a referendum. The referendum never happened though, as a majority in the parliament in 1985 voted against nuclear power and directed the government to conduct energy planning without including nuclear power. The ongoing debate in Denmark throughout the 1960s and 1970s about using nuclear power, among both the public and politicians at that time, had come to an end.

At the same time as the parliament decision on public energy planning without nuclear, a co-generation agreement emphasising small-scale combined heat and power (CHP) plants became a major energy policy priority. In addition, increased priority was given to renewable energy, which led to an agreement in late 1985 between the Danish government and the power producers to install additional wind power capacity. In 1990, politicians agreed on increasing the use of both natural gas-fired CHPs and biomass for heat in district heating. At the same time, they agreed to further increase the installation of wind power.

The transition of the power system that started in the 1980's has today proven to have played an important role in the Danish success with integrating wind power into the power system. As the power plant operators, as result of the political initiatives, started to generate a share of their electricity production from wind power, they quickly discovered an economic benefit in reducing production from the power plants during periods with high wind production. Hence, extending the operational range of the power plants was pursued in order to better regulate the plant's production to fit the variations in wind power production. It is worth noting though, that the motivation to enhance the operational flexibility was not only created by an increasing penetration of renewable energy, but also by changing market conditions, when the power markets were liberalised. Consequently, the first significant optimisation of the conventional power plant operational flexibility was driven by the change of the marked price when entering into the liberalised power market between 1995 and 2000. Today, the most advanced combined heat and power plants in Denmark have an operational range between 10% - 100% of the nominal power. Since the 1990s, the CHP plants in Denmark have thereby been one of the measures to create flexibility in the power system and allow for a large amount of wind power to integrate while keeping the curtailment rate negligible.

The wind industry that arose in the late 1970s was thereby a result of a large public engagement and political goodwill towards the development and expansion of wind power. The first batch-produced Danish wind turbines from the late-1970s had an output of 22 kW and were mainly sold to private families who wanted to cover their own electricity consumption. As the wind turbines gradually scaled up to 55, 75 and

95 kW through the course of the 1980s, many of the turbines were erected by locals organised in wind turbine cooperatives. During the early 1980s the Danish wind industry had likewise experienced a boom in export to California, which at the time had a blooming renewable energy market. This, however, changed as the California wind power market came to a halt in 1985.

In the start of the 1980s, around 20 companies were active in the wind industry in Denmark. However, after the consolidation of the industry through the 1990s, the wind industry became dominated by large, partly internationally owned and listed companies. Since 1995, the majority of wind turbines erected were thereby also owned by people, energy companies and other commercial wind power companies. The only wind turbine manufacturers in Denmark today are Vestas and Siemens (previously Bonus, Nordtank and Micon); both emerged from the wind power development in Denmark in the 1980s.

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2.2 The electrical power system in Denmark today

2.2.1 Historical change

The power system in Denmark has changed significantly in the past 40 years. As a result of the oil crisis in the 1970s, Denmark converted the power system from being heavily based on oil, to heavily based on coal. The power system in the 1980s in Denmark therefore consisted of a few large coal-fired central power stations as seen in the left side of Figure 2-3.

Since the change to a large coal-fired dominated power system, the Danish power system continued to develop over the last 30 years. Particularly over the past two decades the predominant proportion of new capacity being established has been small-scale, decentralised CHP plants and wind turbines. During the 1990s huge investments took place in these new technologies leading to a much more decentralised production, and a huge increase in the number of generating units. During the 1980s and 1990s, many heat-only district heating plants was converted to combined heat and power production, mainly gas fuelled. Government-led heat planning establishing a framework for local authorities enabled this development. An electricity generation subsidy for small-scale CHP plants facilitated the financial incentive to invest in CHP conversion.

The development of new methods for controlling and regulating the power system required the decentralised power production set-up, and provided a more diverse energy mix and hence more security of supply as renewables are less exposed to import constraints and price fluctuations. Hence, a policy structured around diversification of supply, market integration, sustainability and increased energy efficiency through the widespread use of combined heat and power resulted in a current Danish power system with strong interconnectors, distributed power generation from small to medium sized heat and power plants, widely deployed wind turbines, and use of biomass in many large power plants.

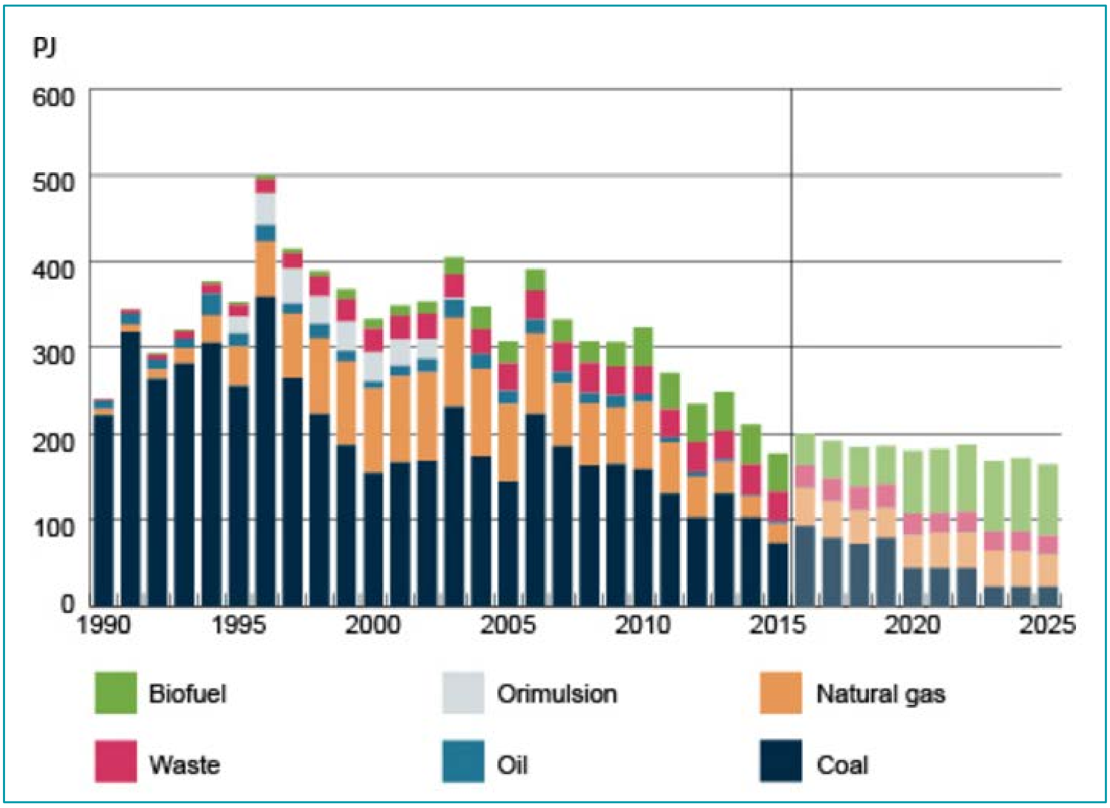

Figure 2-2 Danish Power Station and CHP fuel consumption historically and forecast

2.2.2 Today's power system

The change from the 1980s large coal-fired power system to the current decentralised power system can be seen in Figure 2-3 on the following page.

In 2014, the total installed power generation capacity was roughly 15 GW – including wind turbines. In recent years, thermal capacity declined slightly, and at the end of 2014 was approximately 9.5 GW. Peak load demand has been rather stable for several years around 6.5–6.6 GW. Annual demand in 2015 was 33.6 TWh and has been stagnant or declining since 2010.

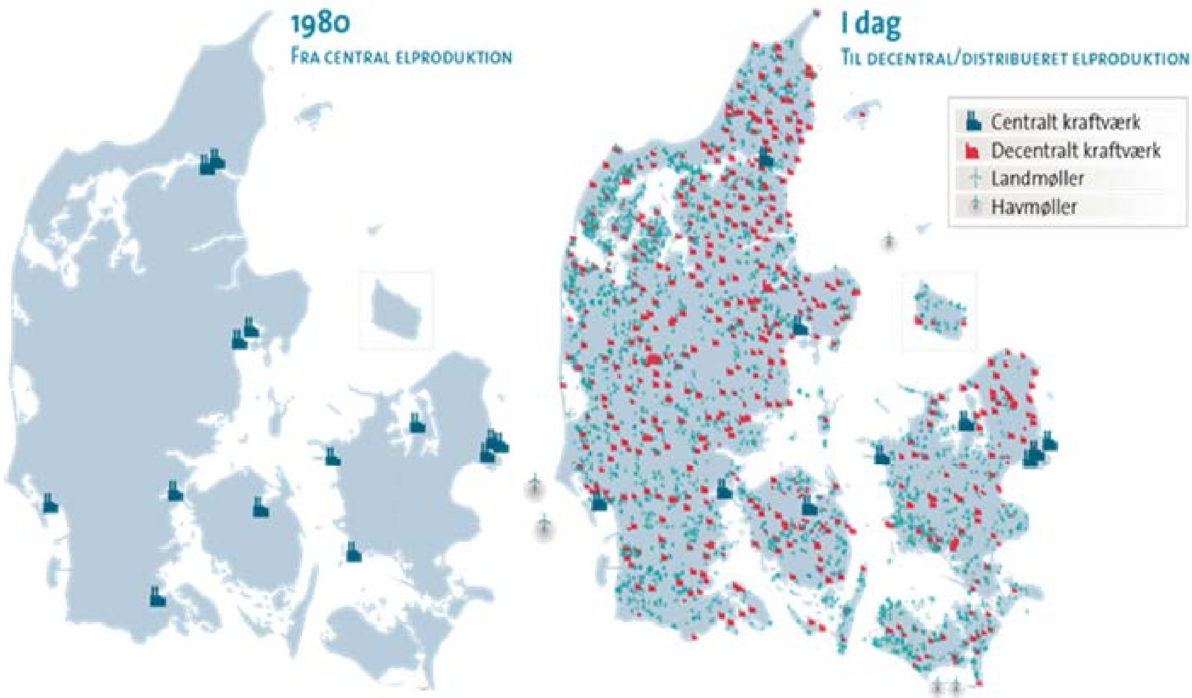

Figure 2-3: The Danish power system. Dominated by central power stations in the 1980s and today changed into a de-centralised power system with large amount of wind power

The internal transmission grid is strong and interconnector capacity to the neighbouring countries is almost equal to peak load (Import capacity from Germany 2.2 GW, Sweden 2 GW and Norway 1.6 GW). The installed power capacity and capacity of interconnectors in Denmark is illustrated in Figure 2-4 together with the maximum and minimum demand range.

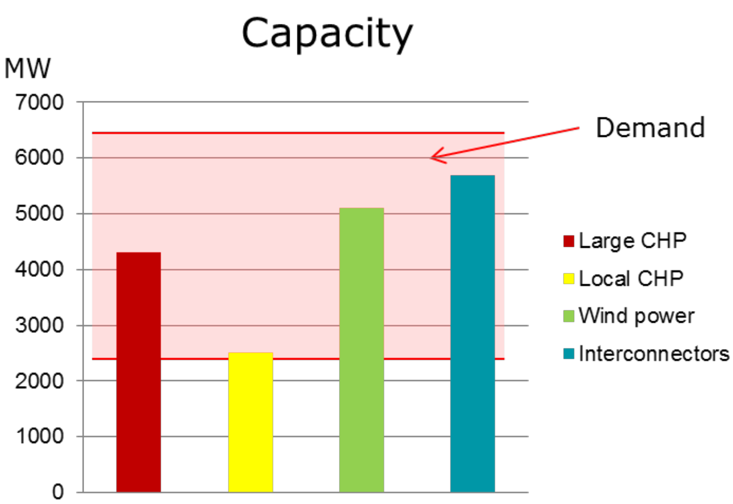

Figure 2-4: Capacity of power generation and interconnectors in Denmark and demand range of Denmark

The Danish power system is divided into two separate power systems, East and West, with a DC interconnection between the two areas, called the Great Belt. The Eastern power system (Zealand) is synchronised with the Nordic power system, also called the Nordic synchronised area. The Western power system (Jutland and Fyn), is synchronised with the continental European system.

2.2.3 Power market and the role of the Danish TSO

Until the late 1990s, Danish electricity production and supply was not regulated by market forces. In the 1980s, wind turbines and other small producers of electricity had obtained a right to sell all of their produced electricity to the large power companies at fixed prices, but apart from that, the Danish electricity sector was in reality a monopoly. In the 1990s, the European Union, which Denmark joined in 1973, embarked on the journey towards creating an inner market for electricity in the EU. This liberalisation process created huge structural changes to the European power sector, driven by the belief that competition would lower electricity prices.

Today the electricity market is fully implemented and well-functioning. The state-owned Transmission System Operator (TSO) “Energinet.dk” carries the responsibility for security of supply and operation of the market, together with its sister organisations in Norway, Sweden, Finland and the Baltic States.

Electricity can be traded both bilaterally between generators/traders and distribution companies/end-consumers/traders and via the Nordic Power Exchange (NordPool). Use of this market system for electricity has eased integration of wind and reduced costs of buying power from abroad. As wind power is sold to the market, the balance of generation serves as cost efficient backup helping to balance supply and demand at all times.

NordPool is a series of international electricity trading markets, incorporating the Scandinavian and Baltic countries. Hourly power contracts for physical delivery during the next 24-hour period are traded in the spot market (NordPool Spot); owned jointly by the Nordic transmission system operators (TSOs). On the spot market the market price is settled for every hour and for every regional area. The spot market (day-ahead market) is considered the world’s most liquid electricity market. The Nord Pool Spot has a market share of 84% in the Nordic region. The Nord Pool Spot exchange also runs an intraday market for physical trade called Elbas. On the Elbas market, electricity can be traded up to one hour before physical delivery. Two other markets also exist: The regulating power market and the reserve capacity market. Sellers and buyers thereby can trade themselves into overall balance through the intra-day market before the TSOs finally ensure the physical system balance via the regulating market.

Due to the cross-border trading both before and after liberalisation, Denmark has strong interconnectors to the neighbouring countries. Theoretically, the interconnector capacity is so high, that Denmark could import close to all of its electricity consumption (as seen in Figure 2-4), with the exception of some of the highest peaks. Construction of even more cross-border interconnector capacity continues, as this is an important prerequisite for integration of a growing share of fluctuating renewables in Denmark, on, and offshore, wind in particular.

According to EU requirements, Denmark has an independent TSO, which is not allowed to own or operate generation capacity. One of the TSOs important roles is to secure a transparent and non-discriminatory day-ahead market as a so-called playmaker. The TSO owns and operates the high voltage network (132 kV up to 400 kV) as well as interconnectors to neighbours. The TSO is now fully state owned, has its own planning with a strategic outlook, as well as strong project management skills in terms of new infrastructure. The structure of the electricity sector is so that all generation is fully commercialised, whereas distribution is a regulated business.

The energy market is described in greater detail in chapter 6.

2.2.4 References

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2.3 Onshore and offshore wind power in Denmark today

The size of wind turbines have undergone considerable scaling since the 1970s. Up to the mid-1990s, the majority of wind turbines erected had an output of 225 kW or less. A large proportion of these have since been replaced by fewer, larger wind turbines under a repowering scheme. Onshore wind turbines in the 1970s and 1980s were often spread out in the landscape, which meant that they affected a very large area with a quite limited installed electrical output. Since 2001 several repowering programmes have been introduced with the aim to incentivise the scrapping of old outdated turbines and have them replaced with new more effective ones placed in a more structured manner and integrated into the overall planning framework.

The number of wind turbines in Denmark peaked in 2000 at more than 6,200 installed turbines, of which more than half were older wind turbines with an electrical output of less than 500 kW. Almost all installed capacity was on land at this time. Since then, the number of wind turbines has decreased by around 1,000, while the total installed output capacity has more than doubled from just below 2,400 MW in 2000, to 5,085 MW by December 2015.

Around 5,200 onshore wind turbines are installed in Denmark today. They are scattered across the Danish territory, although concentrations of turbines are higher in the western part of the country and in coastal regions where wind is ample. Disregarding onshore test sites for offshore turbines, the largest Danish wind turbines onshore today have a capacity of 3.6 MW.

During the last two decades in particular, Denmark has seen a move towards offshore wind. The main driver for Denmark to move offshore is the scarcity of land for onshore sites, and the abundance of shallow waters with ample wind resources. In 1991 Denmark became the first country in the world to take wind turbines out to sea with 11 x 450 kW turbines in the Vindeby offshore wind farm. This was followed by a number of smaller demonstration projects, leading to the first two large offshore wind farms Horns Rev I and Nysted, with outputs of 160 MW and 165 MW respectively.

It is considerably more expensive to build and operate offshore wind turbines than onshore wind turbines. On the other hand, wind production conditions are better at sea with higher wind speeds and more stable wind conditions. The first offshore wind farms in Denmark were built because power companies were given political orders to do so. Today, offshore wind farms are licensed in a competitive tender process, and the cost of producing this electricity is reflected in a feed-in tariff, which is given per kWh produced up to a certain amount of generated electricity.

With almost 1,300 MW offshore wind turbines connected to the electricity grid in 2013, Denmark is still one of the largest developers of offshore wind farms. The largest wind turbine deployed offshore today is 3.6 MW, while 8 MW turbines are undergoing testing.

Figure 2-5 displays onshore and offshore wind sites in Denmark today. The blue colour shows the current areas with offshore and onshore wind turbines. As can be seen from the figure, several offshore areas have been identified for future offshore wind sites.

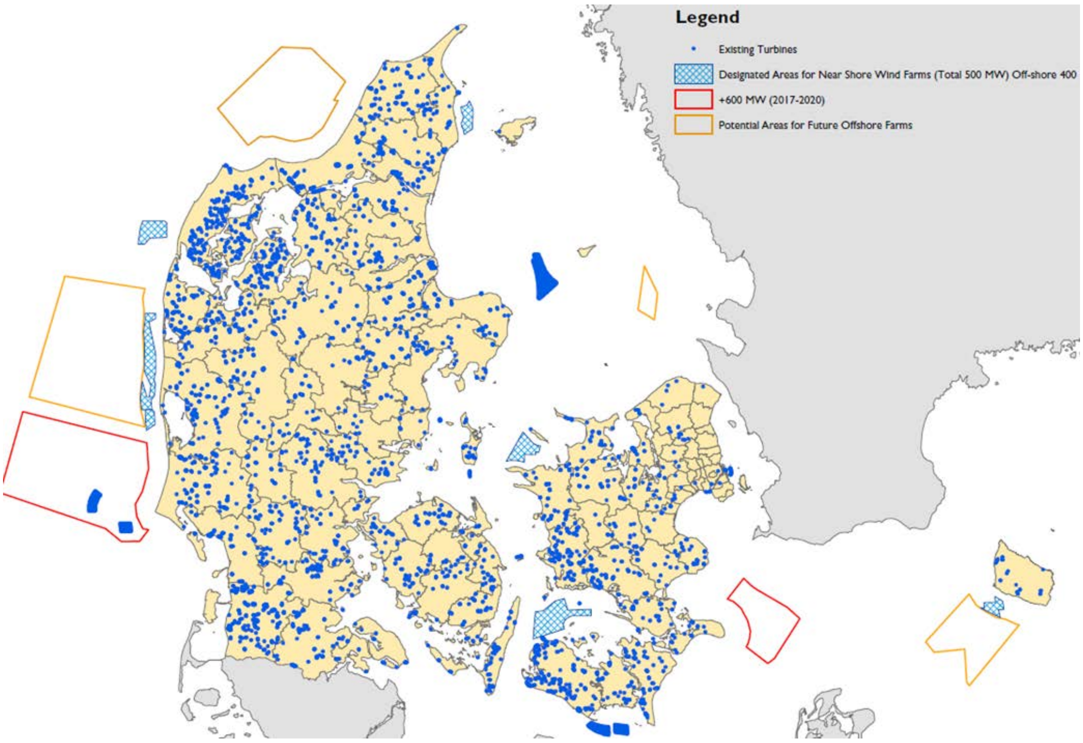

Figure 2-5: Onshore and offshore wind turbines in Denmark

In 2015 there was a total of 3,814 MW onshore wind power capacity in Denmark that produced roughly 9,300 GWh, while a total of 1,271 MW offshore wind power capacity produced around 4,833 GWh, reflecting the higher wind speeds at sea. Hence, approx. 1/3 of the electricity generated by wind turbines came from offshore turbines and 2/3 from onshore turbines.

The wind power generation relative to the domestic electricity consumption has grown steadily since 1980. In 1990, the share was 1.9%, and since then it has increased sharply. In 1999 the figure topped 10%, and in 2010 it reached 22% of the electricity demand. In 2015 the wind penetration amounted to 42% of Danish power consumption. Figure 2-6 shows the wind deployment as a percentage of national power demand from 2005 to 2015. In 2020, the target is to have 50% of the Danish electricity demand covered by wind power.

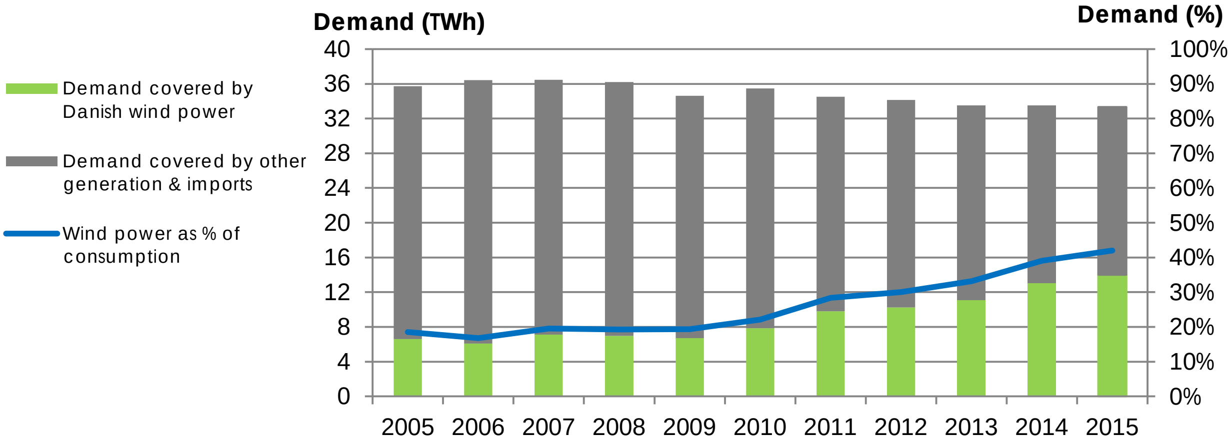

Figure 2-6: Development in wind power from 2005-2015 in Denmark in relations to the electricity consumption in Denmark.

2.4 The relevance of Danish experience for Indonesia

Denmark is a small country compared to Indonesia and the Danish power system is well connected to the larger European power grid. This could potentially lead to the conclusion that Danish experiences from integration of renewables are hardly replicable to Indonesia, which is a large country with no or weak connections to neighbouring countries, and even within the country. However, many facilitating factors for integration of fluctuating renewables enjoyed by Denmark, such as transmission and interconnectors, flexible generation units, as well as forecasting and operational planning tools can be replicated wholly or partly within parts of Indonesia such as the Java-Bali system.

The Danish power system with an annual demand of around 32 TWh is considerably smaller than the Indonesian with an annual consumption of approximately 158 TWh, and therefore more dependent on connection to neighbouring countries. Indonesia, without the option to benefit from connection to neighbouring countries' power systems, might be able to find important resources within the country. The Java-Bali system with its annual consumption of approximately 127 TWh is an example of this. For comparison, the Nordic power system (Denmark, Norway, Sweden and Finland) has a total annual consumption of around 380 TWh, and Denmark's neighbouring power system to the South (Germany) has an annual consumption of around 520 TWh.

Table 2-1serves to illustrate the proportions as does the map in Figure 2-7, showing that Indonesia covers a large share of the EU if superimposed on a map of Europe. Total area of the EU (including UK) is 4,324,782 sq. km.

	Indonesia	Java+Bali	Denmark	Multiples, Indonesia compared to Denmark	Multiples, Java-Bali compared to Denmark
Area [sq.km]	1,905,000	155,780	43,100	43.1	3.6
Population [m]	262	154	5.6	46.8	27.5
Annual Electricity Consumption [TWh]	158	127 (est.)	34	4.6	3.7

Table 2-1: Comparison of key numbers for Denmark and Indonesia. Sources: Estimates based on Wikipedia and ENTSO-E for data on power system demand.

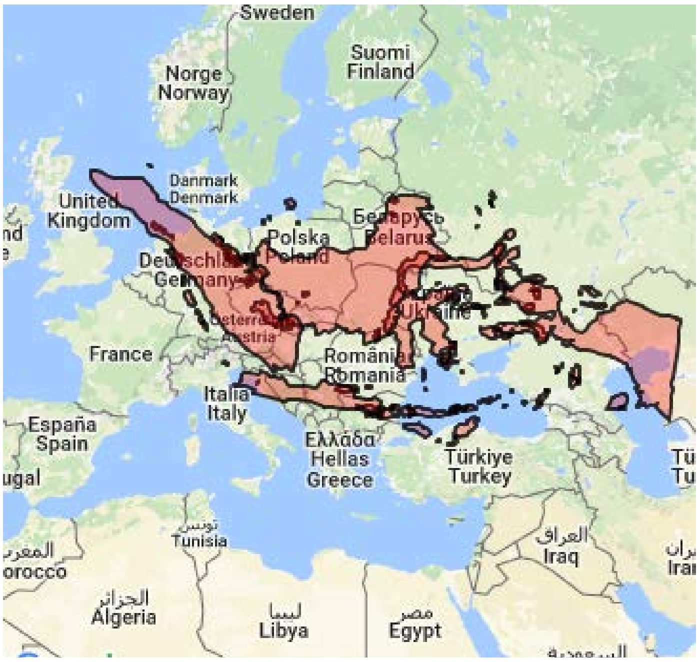

Figure 2-7: Area wise scale of Indonesia compared to Denmark and Europe. Source: www.ifitweremyhome.com

2.4.1 References

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3 Power generation from wind turbines

This chapter focuses on wind as a power generation source and how to utilise this natural source. The typical characteristics of wind power generation are discussed looking at the power curve of a wind turbine and the capacity factor. The chapter also presents the official IEC wind turbine classes and illustrates with an example, using the Weibull distribution of wind speeds at one site in Denmark, the importance of choosing the optimal turbine for a specific site. The final section of this chapter will focus on the wind resources in Indonesia and discuss how low speed wind turbines can be suitable for Indonesian requirements.

3.1 Characteristics of wind power generation

A wind turbine is a machine that converts the kinetic energy of wind into electricity. A modern wind turbine consists of a rotor (the Danish design has three blades) that drives a generator producing electricity. The rotor and generator are installed at the top of a tower, which stands on a foundation in the ground or in the seabed. The turbine cap (nacelle) and the blades are controlled based on measurements of the wind direction and speed.

In simple terms, a wind turbine not only utilises the wind's pressure on an obliquely positioned blade, but also utilises the fact that the air current around the blade creates a negative pressure on the rear of the blade in relation to the wind. The force from this negative pressure produces a draught that causes the blades to rotate.

The aerodynamic power of a wind turbine can be expressed by the equation below. It reflects how much power is possible to extract from the wind. The aerodynamic power is a function of the air density σ, the wind turbine's rotor area *A*, the wind speed *U,* and the aerodynamic efficiency C_p. The aerodynamic efficiency can theoretically not exceed the Betz limit of 59%. It can be expressed as a function Cp(λ;θ), hence, it depends on the pitch blade angle θ (angle between the chord line and the tip speed) and the tip speed ratio λ (ratio between tip speed and wind speed). Therefore, if the wind turbine enables it, the aerodynamic efficiency can be controlled by adjusting the pitch angle and the rotor speed.

$$P = \frac{1}{2} \sigma \, A \, U^3 \, C_p$$

As seen by the equation, the power production of wind turbines will increase if the rotor area (*A)* increases and/or if the wind turbine is put in an area with higher wind speeds (*U*). The increase of rotor area is clearly seen in the production of wind turbines in the past decades, as illustrated in Figure 3-1.

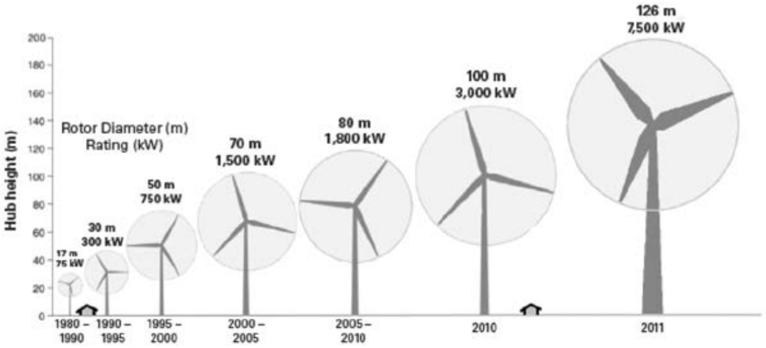

Figure 3-1: Rotor area of wind turbine since 1980

The actual power output of a wind turbine is limited by physical restrictions and is best illustrated by a power curve. The power curve of a wind turbine shows the electrical power output of the wind turbine at specific wind speeds. An example of a power curve is shown in Figure 3-2. It represents a Vestas V117-3.3 wind turbine; hence, the turbine has a rotor diameter of 117 meters and a nominal power of 3.3 MW.

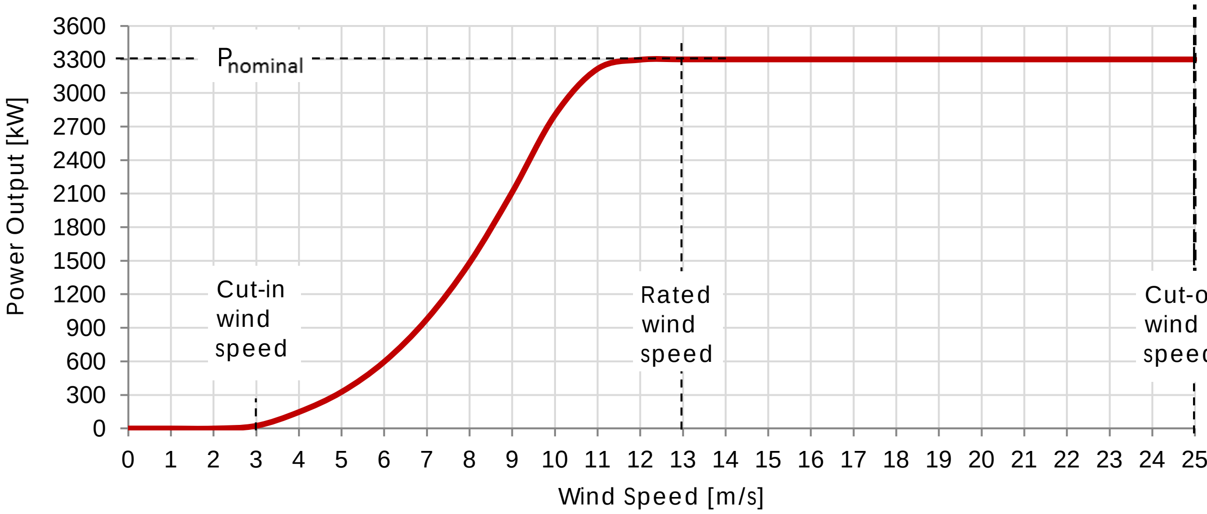

Figure 3-2: Power curve of a wind turbine. Example shows the Vestas V117-3.3 turbine

The operating range of the wind turbine is defined by the cut-in and cut-out wind speeds. The cut-in wind speed is the sufficient wind speed for the generator to operate and produce electric energy, for the V117-3.3 turbine its 3 m/s as shown in the power curve. When the cut-out wind speed is reached the power production of the wind turbine is cut off, hence, at 25 m/s for the V117-3.3 turbine. The rated wind speed is the wind speed at which the rated nominal power of the wind turbine is reached. The nominal power of 3.3 MW for the V117-3.3 turbine is reached at 13 m/s. The wind meter on the individual turbine informs the turbine's control system when the wind speed reaches the cut-in or cut-out wind speed.

The rated nominal power of the wind turbine is thus the maximum output that a wind turbine can produce, and in popular terms referred to as the turbine size. For example, a wind turbine of 3.3 MW can thus produce a maximum output of 3.3 MW, typically at wind speeds of 15-25 metres per second. At maximum production, the turbine produces 3.3 MWh (3,300 kWh) in one hour, roughly equivalent to the annual electricity consumption of an average Danish family living in an apartment.

In order to avoid mechanical stresses, which potentially could destroy the wind turbine, the power is kept at nominal output once the rated wind speed is reached and the production of the turbine is stopped when the cut-out wind speed is reached. Hence, this zone between the rated and the cut-out wind speed is called the limitation zone, and the wind turbine is designed and controlled to limit its output power within the limitation zone. The limitation of the output power within the limitation zone is achieved by reducing the efficiency of the energy conversion of the wind's kinetic energy into mechanical energy, through for example adjustment of the pitch angle and the tip speed ratio. The zone between the cut-in wind speed and the rated wind speed is the optimisation zone where the wind turbine is designed and controlled to optimise the aerodynamic efficiency.

The capacity factor can be used to assess how efficient a site is. It is defined as the average power output of a wind turbine or wind farm as a percentage of the nominal power of the turbine/wind farm. The capacity factor can be expressed by the equation below, where AEP is the annual electricity production from a wind turbine/wind farm, and P_{nom} is the theoretical power output if the wind turbine/wind farm produced at nominal power for an entire year.

$$Capacity\ factor = \frac{AEP}{P_{nom} * 8760h}$$

For most wind turbines erected on land, the capacity factor is between 20-40%, or expressed in full-load hours it is around 1,800-3,500 h/a. Very good wind sites on land and offshore wind farms can generally reach a higher capacity factor of 45-60%, or even higher.

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3.2 Turbine design parameters for specific wind sites

Different wind sites can have very different wind resources. Wind turbines are therefore designed for specific wind conditions. When planning a wind power plant one of the areas to look into is the turbine wind class of the sites. IEC 61400-1 is an international standard for wind turbine generator classes published by the International Electrotechnical Commission. Manufacturers design different machines according to the classification. The turbine classes are determined by parameters of turbulence and wind speed. The basic parameters that determine the turbine classes are specified in Table 3-1. Category S is used for values specified by the developer which fall outside of the general categories (e.g. some offshore wind turbines).

The roman number defines reference wind speed V_{ref}. Hence, the reference wind speed with class I, II and III represent sites with the high, medium and low wind speeds, respectively. In the standard wind turbine classes, the average wind speed is $V_{ave} = 0.2* V_{ref}$ and the extreme 50-year wind speed is likewise a function of V_{ref} (and hub height). The extreme 50-year wind speed is the wind speed which is statistically exceeded once in 50 years.

The letter of the turbine classes defines reference turbulence I_{ref}. Hence, the turbulence intensity with class A, B and C represents sites with higher, medium and lower turbulence characteristics, respectively. The turbulence is dependent on for example surface roughness, terrain and surface heat flux.

The optimal turbine for a site matches the local wind conditions as well the prevailing regulatory framework. For example, a turbine class of I-B is designed for high wind speeds and moderate turbulence.

Table 3-1: IEC 61400-1 Wind Turbine Class

Wind turbine class		I	II	III	S
V_{ref}	(m/s)	50	42,5	37,5	Values
A	I_{ref} (-)		0,16		specified
B	I_{ref} (-)		0,14		by the
C	I_{ref} (-)		0,12		designer

The wind resources at different sites can be analysed by using the Weibull distribution. The Weibull distribution gives an approximation of the wind speed distribution at specific sites. It shows a graph where the frequency of the wind speed at a specific site is plotted as a function of the wind speed. Hence, it shows the frequency distribution of wind speeds, and mathematically it can be described as a function depending on two site-specific parameters: *a* and *k*. The two parameters *a* and *k* are specific for the site investigated and are generally obtained via measurement of wind speed using an anemometer on the site. *a* is the Weibull scale parameter and *k* is called the Weibull form parameter.

The Weibull distribution for a particular site in Denmark, Hvide Sande, is shown in Figure 3-3. The Weibull parameters for Hvide Sande are *a* = 7.81 m/s and *k* = 2.23, with a mean wind speed of 6.9 m/s.

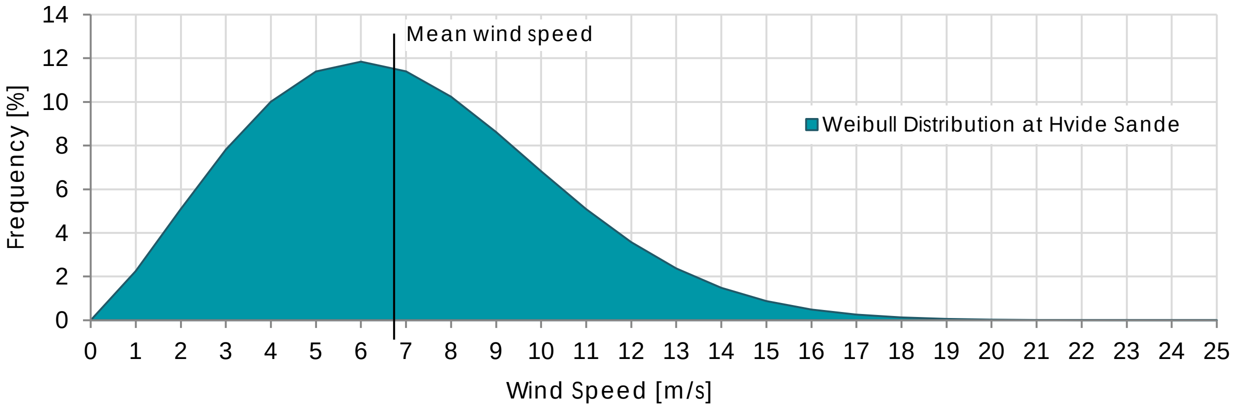

Figure 3-3: Weibull Distribution of the wind speeds at the Danish site Hvide Sande

Combining the power curve in Figure 3-2 and the Weibull distribution of the Danish site Hvide Sande, the capacity factor of the Vestas V117-3.3, if erected on the Danish site, can be estimated. Neglecting all losses, the estimated annual energy production (AEP) of one turbine (V117-3.3) at Hvide Sande is 10,876 MWh with a capacity factor of 37%.

It is important to note that the losses are neglected in this AEP calculation. In reality, the AEP also depends on wake losses (if other turbines are erected on same site), losses in the internal grid of the wind farm, and potential outages within the time period considered, as illustrated in Figure 3-4.

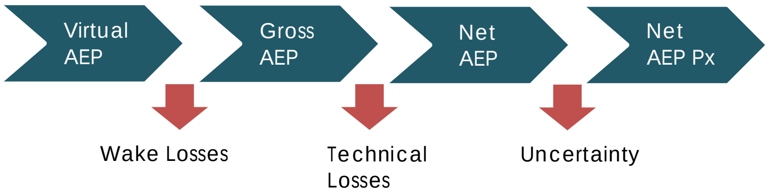

Figure 3-4: Losses in a wind farm

The Vestas V117-3.3 has the IEC class IIA and is thereby optimised for usage at moderate wind sites. If on the same site at Hvide Sande the Vestas V126-3.3 (rotor diameter 126m, nominal power 3.3MW) wind turbine was erected, neglecting losses, the capacity factor can instead be estimated to be 41%. Despite the exact same nominal capacity of the two Vestas turbines, the capacity factor of the wind site at Hvide Sande becomes higher with the V126-3.3 turbine. The reason can be explained by looking into the power curve and wind class of the V126-3.3 turbine in comparison to the V117-3.3 turbine.

The wind class of the V126-3.3 turbine is IIIA; hence it is optimised to fit low wind speed sites. This is also confirmed by the power curve of the V126-3.3 turbine. The power curve of the V126-3.3 turbine is shown in Figure 3-5 together with the power curve of the V117-3.3 turbine. Both turbines have the same cut in wind speed at 3 m/s, however at lower wind speeds during the optimisation zone the V126-3.3 turbine has a higher power output compared to the V127-3.3 turbine, and similarly the V126-3.3 turbine reaches its rated power at 12 m/s instead of 13 m/s as the V117-3.3 turbine does. Hence, the V126-3.3 turbine is able to produce more electricity at lower wind speeds compared to the V117-3.3 turbine. However, the cut-out wind speed for the V126-3.3 turbine is at 22.5 m/s and will therefore stop production during higher wind speeds earlier than the V117-3.3 turbine (cut-out wind speed of V117-3.3 turbine is 25m/s).

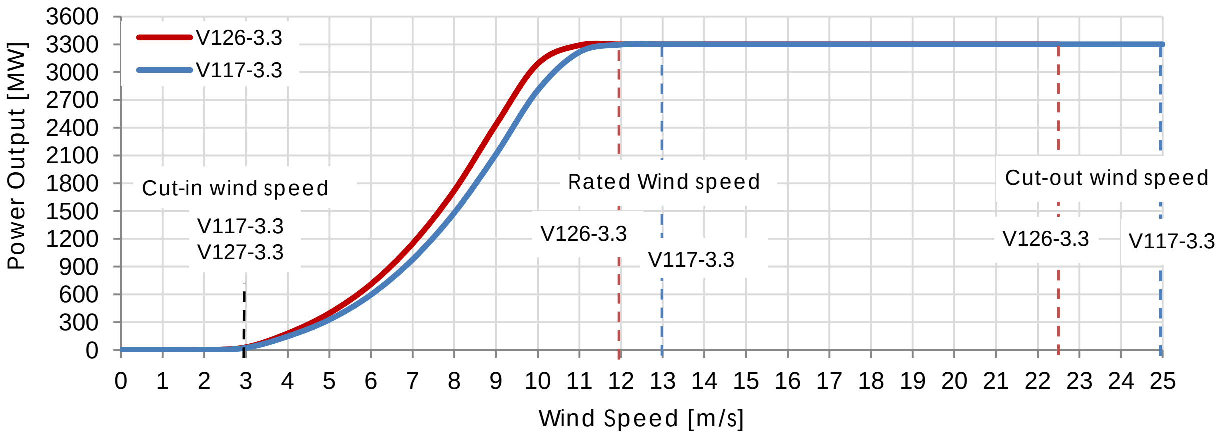

Figure 3-5: Power curve of the V117-3.3 turbine and the V126-3.3 turbine

In looking at the frequency of wind speeds at the Danish site Hvide Sande (Figure 3-3); it is only during very rare moments that the wind blows at wind speeds higher than 20 m/s. As such, the fact that the cut-out wind speed is at 22.5 m/s for the V126-3.3 turbine will only have very little effect on the AEP and capacity factor for this turbine on the Hvide Sande site. Similarly, there is a high frequency of wind speeds during the optimisation zone, where the V126-3.3 has a higher power output compared to the V117-3.3 turbine, which all in all leads to the higher estimate for the capacity factor if the V126-3.3 turbine is used on the Danish site of Hvide Sande.

This example, comparing the V117-3.3 to the V126-3.3 turbine, illustrates the importance of choosing the optimal wind turbine to a specific site depending on the wind characteristics of the site. Other parameters are also important to consider when choosing the wind turbine for a site, such as the generator type, the compliance with grid codes, mechanical and aerodynamic noise of a turbine, transportation of equipment, etc.

3.2.1 References

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3.3 Economy of modern wind power

3.3.1 Levelized Cost of Energy

When assessing the electricity generation cost of different technologies, the *Levelized Cost of Energy (LCoE)* is a useful indicator. LCoE estimates the average lifetime cost of power production per MWh. The cost elements comprising the LCoE include investment costs, fuel costs, operation and maintenance costs, environmental externalities, system costs, and heat revenue for combined heat and power plants (Danish Energy Agency and Ea Energy Analyses 2016). However, it is important to acknowledge that while LCoE can give good estimates for the cost of power generation, it cannot replace system analyses, which is able to capture the interdependence between technologies.

As a part of Denmark's international cooperation, the Danish Energy Agency (DEA) in cooperation with Ea Energy Analyses has developed a Levelized Cost of Energy Calculator - LCoE Calculator - to assess the average lifetime costs of providing one MWh for a range of power production technologies or power savings[1]. Important assumptions included in the LCoE calculator include technology definitions, as well as cost of fuel and emissions (Table 3-2).

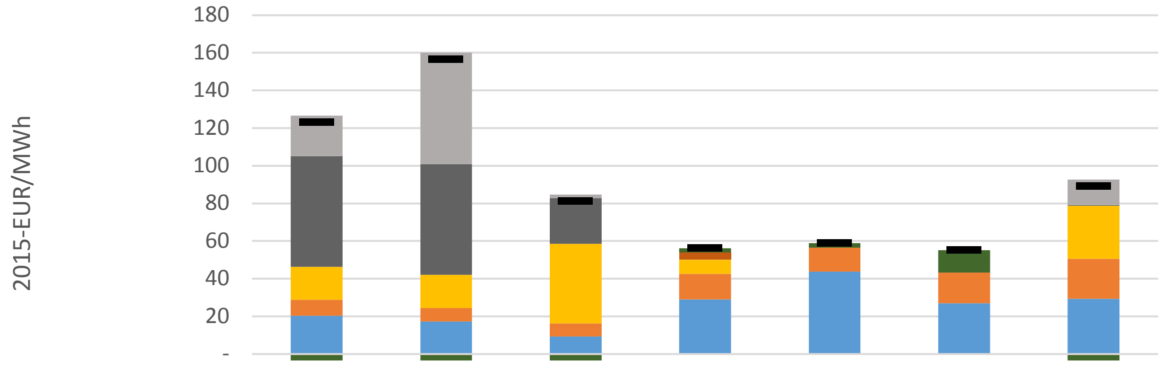
Category	Elements
Technical data	-Energy efficiencies -Cogeneration efficiencies (power and heat) -Lifetime -Construction time -Emission factors
Full load hours	-Assumptions for estimated dispatch of base load plants for thermal power generation -Assumptions for resource quality for variable renewable generation
Discount rate	- Discount rate is used to determine the present value of future costs and Revenues
Capital cost	-Investment cost of the plant and new or upgraded infrastructure if needed
Operation and maintenance (O&M)	-Fixed O&M (Annual cost independent of generation) -Variable O&M (Dependent on amount of generation)
Fuel cost	-Projected costs of fuels according to IEA World Energy Outlook 2015
Heat revenue	-The earnings from heat sale (only applies to combined heat and power plants)
System costs	- Balancing costs – Costs of handling deviations from planned production - Profile costs – The value of electricity generation compared to a common benchmark, such as the average electricity market price. - Grid costs – Costs for expanding and adjusting the electricity infrastructure.
Climate	-CO_2 emission valued according to projected costs in IEA World Energy Outlook or a custom figure. - CH_4 emissions converted to CO_2 equivalents and valued as such. - N_2O emissions converted to CO_2 equivalents and valued as such.
Air pollution	- SO_2 – Socio-economic costs of SO_2 emissions - NO_X – Socio-economic costs of NO_X emissions - PM2.5 – Socio-economic costs of PM2.5 emissions
Other costs	Radioactivity – Socio-economic cost of radioactivity - Further external costs, can be defined by the user

Table 3-2: Elements and assumptions included in the LCoE calculator. Adapted from Ea Energy Analyses and Danish Energy Agency (2016).

Based on international technology data and fuel price projections by the International Energy Agency, the standard calculation for 2020 as the first year of operation shows that renewable energy from wind and

[1] The calculator is available for free download including introduction and manual at https://ens.dk/en/our-responsibilities/global-cooperation/levelized-cost-energy-calculator

solar power is competitive with fossil alternatives from a socioeconomic perspective (Figure 3-6). As technology data are based on IEA projections from 2015, the cost estimates for wind and solar power do not take into account the cost development for especially wind and solar power indicated by both Danish and worldwide auctions. This could lead to further cost reductions for solar power and offshore wind.



	Coal FGD INT	Coal no FGD INT	Natural gas CCGT INT	Nuclear INT	Solar PV INT	Wind onshore INT	Biomass plant INT
Heat revenue	-	-	-	-	-	-	-
System costs	-3	-3	-3	2	2	12	-3
Air pollution	22	59	2	-	-	-	14
Climate externalities	59	59	24	-	-	-	0
Other costs	-	-	-	4	-	-	-
Fuel cost	18	18	42	7	-	-	28
O&M costs	8	7	7	14	13	16	21
Capital cost	20	17	9	29	44	27	29
Total LCOE	123	157	81	56	59	55	89

Figure 3-6: LCoE for key technologies. Key Assumptions: First year of operation: 2020, Technology data primarily from "Projected cost of generating electricity 2015" (IEA, 2015). Fuel and emission cost based on World Energy Outlook 2015, 450 ppm-scenario. Annual full-load hours for coal, gas and biomass technologies: 5,000, nuclear power: 7,000, wind power: 3,000, solar PV: 1,700. Discount rate: 4% real. FGD: flue gas desulphurisation. System costs for wind and solar power depend on penetration level and are based on Danish experiences.

3.3.2 An illustrative example for the Indonesian context

Assessments of LCoE for different technologies in the Indonesian power system need to take into account the Indonesian context. For technology data, this concerns especially the investment cost. For wind and solar power, the quality of the resource has to be taken into account. In order to give an illustrative example, the following data have been adjusted in an attempt to give a better picture of LCoE in the Indonesian context:

- Technology cost and data based on IEA-data for India

- o Wind technology costs have been increased by 10% pr. MW to account for the low specific power turbine applied.[2]
- o The wind power generation based on the wind speed resource is estimated using the power curve for a Vestas V126 3.3 MW, which is a low wind speed turbine with a rotor diameter of 126 m.
- o The system integration cost for wind power is reduced to around 2.2 EUR/MWh, as integration cost at low penetration levels are lower.

- Fuel costs are based on the New Policy Scenario in the World Energy Outlook 2015 for South East Asia.
- Wind resources are based on good locations from the Wind Atlas developed by EMD International A/S funded by Danida (see section 3.4 and Figure 3-7)
  - o Capacity factor Southern Sulawesi: 41%, 3,580 Full load hours
  - o Capacity factor Central Java: 34%, 3,000 Full load hours
- Solar resource set to 1,500 full load hours, based on www.renewables.ninja, which is a web service enabling extraction of wind and solar generation series based on meteorological data based on reanalysis data. The International Energy Agency estimates global horizontal radiation to be between 1,600 and 2,200 kWh/m^2, corresponding to 1,200-1,650 full load hours at a performance ratio[3] of 75%.

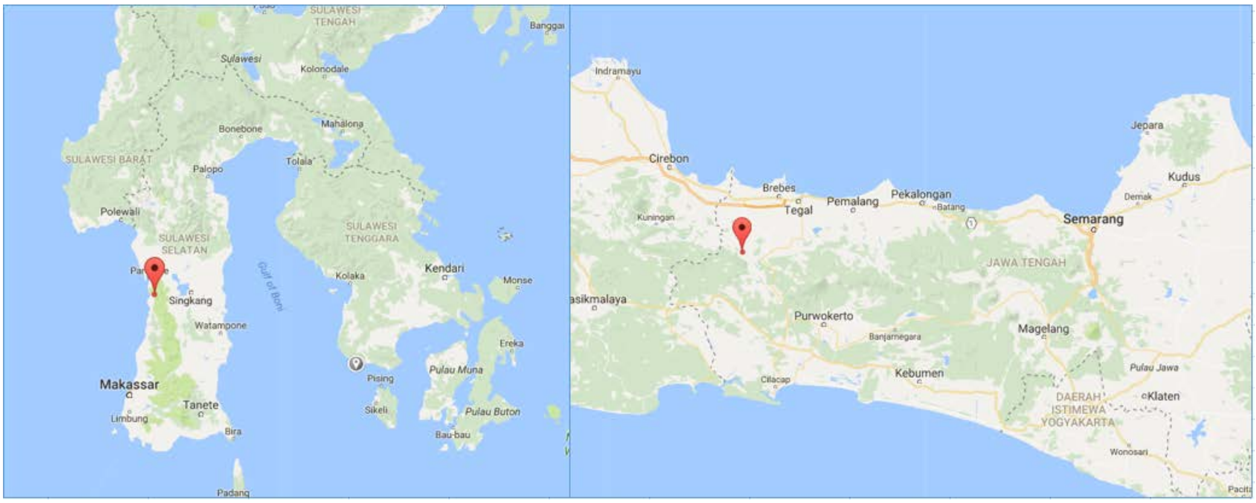
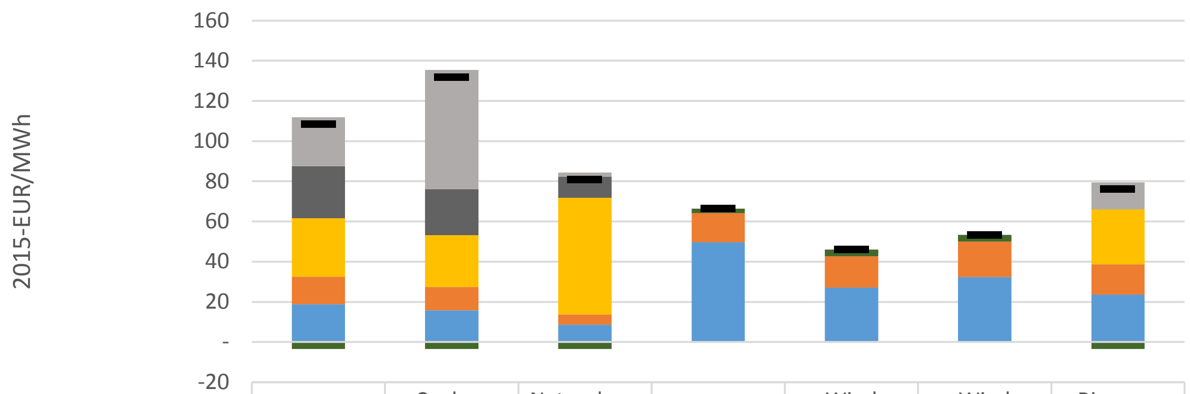


Figure 3-7: Chosen locations for wind resource on Southern Sulawesi and Central Java. The average wind speed for the two locations is 6.9 and 6.0 m/s respectively.

Similar assumptions are also used in scenario work carried out by the National Energy Council of Indonesia, but are subject to further evaluation and should only be seen as indicative numbers. Technology costs do not include supply cost specific to Indonesia, such as both transport, installation and O&M considerations for remote locations. Furthermore, any necessary grid reinforcements are not included.

[2] The estimate is based on indications in *IRENA, Renewable Power Generation Costs in 2014. Technical Report January, 2015.*
[3] Performance ratio for solar PV plans is the ratio of the actual and theoretically possible energy outputs, thus defining the possible generation to the grid after deduction of internal losses.

The calculations for LCoE of different technologies for Indonesia are only illustrative, but clearly show an economic perspective for wind power on good locations in Indonesia from a socio-economic perspective (Figure 3-8). The development of wind power technology means that also lower wind speed sites can give a reasonable number of full load hours, reducing the electricity generation cost. Recent cost development for solar power will make solar power more competitive than indicated. Furthermore, this report does not include a detailed analysis of the solar resource, which could lead to further cost reductions.



	Coal FGD Indonesia	Coal no FGD Indonesia	Natural gas CCGT Indonesia	Solar PV Indonesia	Wind onshore Sulawesi	Wind onshore Java	Biomass plant Indonesia
Heat revenue	-	-	-	-	-	-	-
System costs	-3	-3	-3	2	3	3	-3
Air pollution	24	59	2	-	-	-	13
Climate externalities	26	23	11	-	-	-	0
Other costs	-	-	-	-	-	-	-
Fuel cost	29	26	58	-	-	-	27
O&M costs	14	12	5	14	16	18	15
Capital cost	19	16	9	50	27	32	24
Total LCOE	108	132	81	66	46	53	76

Figure 3-8: Illustrative example of LCoE for key technologies in Indonesia. First year of operation: 2020,

3.3.3 Wind data for a real life business case for a wind farm

Building a business case for a wind farm is no trivial task. The complexity depends on for example the certainty required by investors and financiers.

Typical cases all require on-site wind measurements for a minimum of a full year. However, the length of the measurement campaign again depends on e.g.:

- The accuracy and characteristics of measurement equipment used
- Data outages (if any)
- Availability and accuracy of nearby long-term reference measurements (meteorological stations, airports etc.)

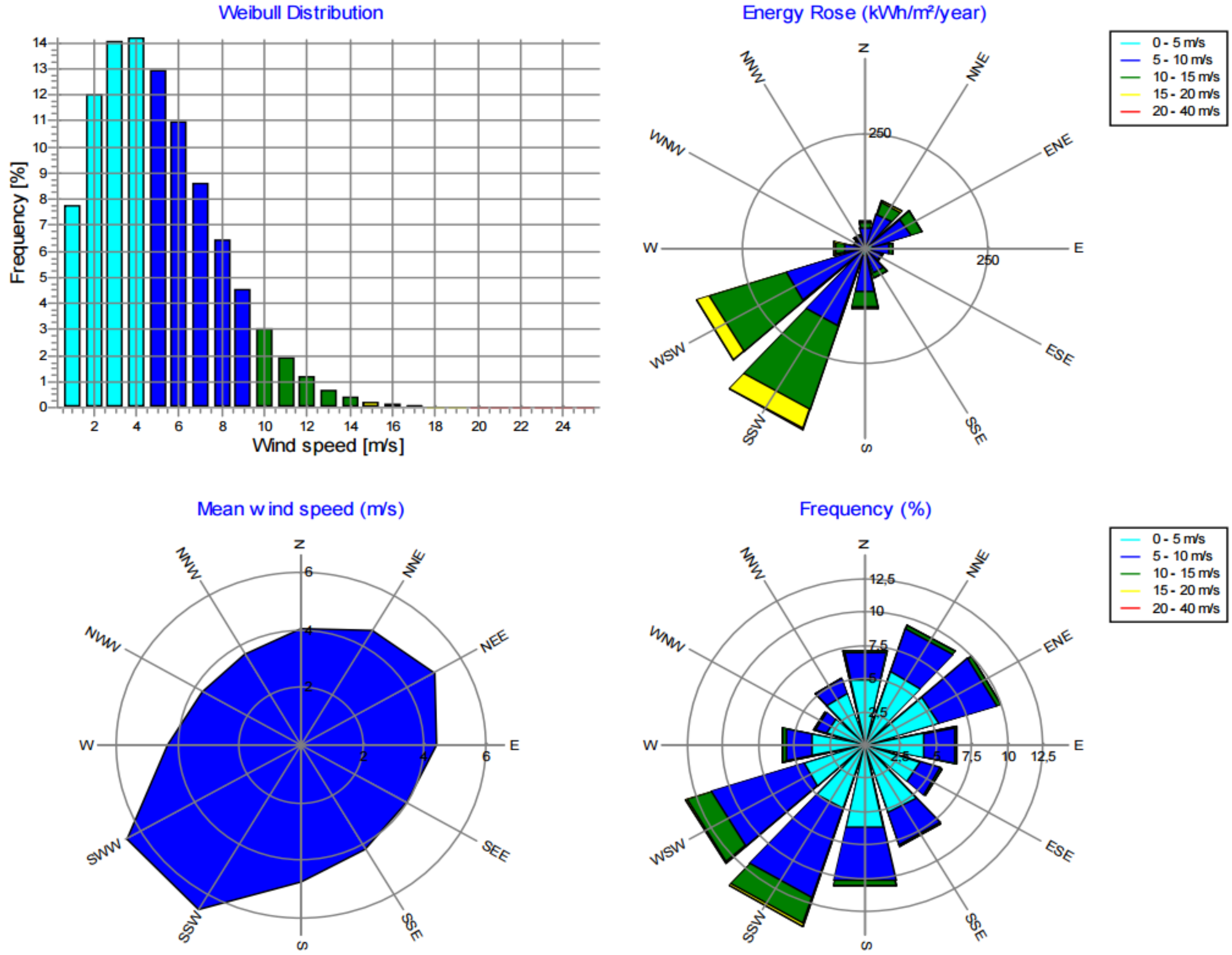


Figure 3-9: Some results from sample wind study produced by the tool WindPro.

Reference time series are used to establish a "normal" year's wind resource, equivalent to an average site-specific wind resource over 10-50 years. Without such long-term data, it is not possible to establish if on-site measurements represent e.g. an 80% wind year or a 120% wind year.

An investment grade wind study will include a choice of suitable wind turbines for the site, an optimal micro-siting of turbines on the available plot of land as well as the Annual Energy Production (AEP) for the chosen turbines.

AEP will typically be expressed in terms of a P50 number (likelihood of undershooting equals likelihood of overshooting, median) as well as a P90 number (likelihood of overestimating AEP reduced to 10%). Some conservative financiers prefer to use the P90 AEP when analysing a business case for a wind farm.

3.3.4 References

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3.4 Discussion – low speed wind turbines

The National Institute of Aeronautics and Space (LAPAN) was among the firsts to investigate the wind potential of Indonesia. Out of 166 sites investigated, LAPAN identified 35 good wind sites in Indonesia with wind speeds greater than 5 m/s at 50 meters height. These areas were concentrated in West Nusa Tenggara, East Nusa Tenggara, the south coast of Java and South Sulawesi. In adjacent to this, LAPAN also identified 34 sites with a fair wind potential of 4-5 m/s.

In 2014, the first wind map of Indonesia was developed by EMD International A/S, Denmark, funded by ESP3, Danida. The mesoscale map had been developed to support the identification of wind energy projects and was launched by MEMR. The resolution of the map is 3 km. The map is electronically accessible to the public (http://indonesia.windprospecting.com/).

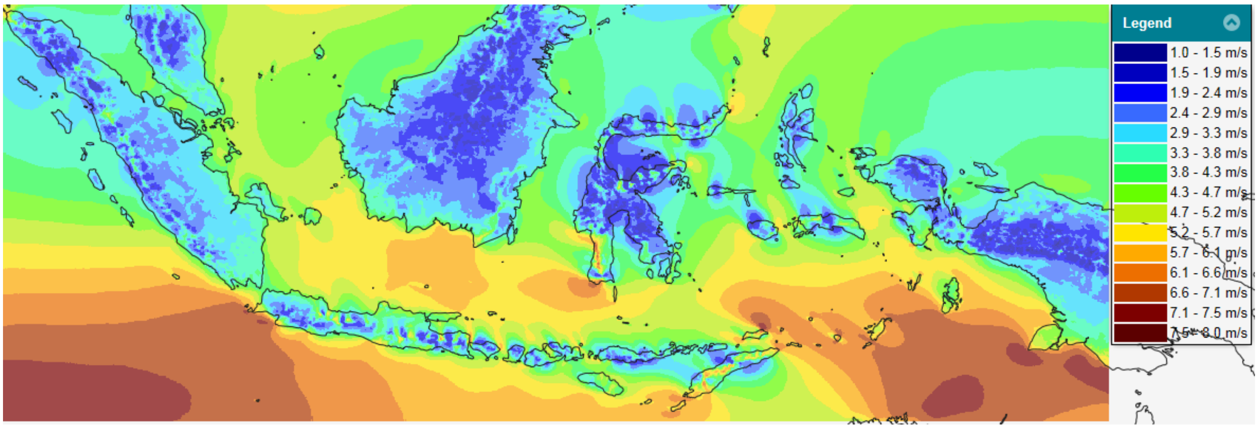

Figure 3-9: Wind map of Indonesia

Overall, the wind speeds in Indonesia are generally low; however, as the study conducted by LAPAN showed, a number of wind sites with good potential for wind energy projects do exist. On average, the wind speeds are around 3-7 m/s and MEMRs estimated installed capacity potential to be 9.29 GW. Currently, around 3 MW of wind power is installed, and there is a great potential of increasing the wind power capacity in Indonesia.

The wind resources in Indonesia generally fit the design of low speed wind turbines. In recent years, wind turbine manufacturer have focused on expanding their portfolio of turbines suitable for low wind speed sites. The development towards low speed wind turbine has been driven partly by limited available sites with high wind speed potential, and partly by advancement in wind technology. To make turbines cost effective at low wind speed sites, turbine manufacturer have mainly focused on increasing the capacity factor by reducing the rotor specific power, hence increasing the rotor diameter for the same turbine rating. Doing so, the turbine produces more power at lower wind speeds and the power curve of the turbine is thereby shifted to the left. This is also seen in Figure 3-5 with the example comparing the V117-3.3 to the V126-3.3 turbine.

Similarly, the tower height of wind turbines has continuously increased in recent years as seen in Figure 3-10. The benefits of higher towers are that they both allow enough ground space to install larger rotor area, and at the same time, the wind resources are better, as it for example reduces surface disruptions. In some countries such as Denmark, restrictions on maximum height prevent this development.

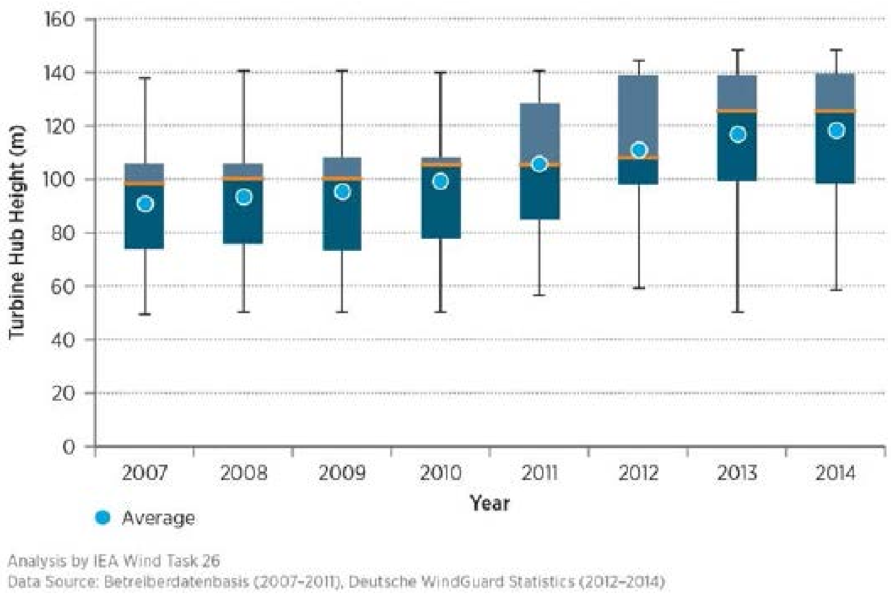

Figure 3-10: Wind turbine tower height in Germany from 2007 to 2014

The gained increase in capacity factor of turbines erected at low speed wind sites often outweighs the extra capital cost associated with increasing the rotor diameter and tower height, and therefore makes wind power economically feasible at low wind speed sites. The development in turbine technology has thereby also made it possible to utilise the wind potential in different locations in Indonesia. The barriers for developing wind power in Indonesia are thereby concentrated on local regulatory and technical challenges. Several wind farm developers have likewise seen the potential of expanding wind power in Indonesia and with the current work from both wind farm developers and governmental institutions in Indonesia, the first commercial wind farm projects in Indonesia are likely to be online in the foreseeable future.

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4 Policy and regulatory measures for promotion of wind power in Denmark

This chapter will discuss the political strategies undertaken in Denmark to accelerate wind power development by looking into both historical and current regulations and subsidy schemes used to promote wind power. The chapter will provide an overview of Danish experiences with respect to the financing of subsidies for wind power and the management of wind resource data. The chapter will end with a discussion of some of the regulatory challenges in Indonesia to address to enhance the development of wind power in Indonesia.

4.1 Political strategies undertaken in Denmark to accelerate wind power

4.1.1 First political initiative

Denmark's energy policy took shape after the oil crises of the 1970s. When oil prices accelerated in 1973 Denmark was among the OECD countries most dependent on oil in its energy supply. More than 90% of all energy supply was imported oil. As a consequence, Denmark launched an active energy policy to ensure the security of supply and enable Denmark to reduce its dependency on imported oil.

Denmark chose early on to prioritise energy savings (energy efficiency) and a diversified energy supply, including use of renewable energy. A broad array of notable energy-policy initiatives were launched, including a focus on combined heat and power production, municipal heat planning and on establishing a more or less nation-wide natural gas grid. Furthermore, Denmark extensively improved the efficiency of the building mass, and launched support for renewable energy, research and development of new environmentally friendly energy technologies as well as ambitious use of green taxes. In combination with oil and gas production from the North Sea, the policy meant that Denmark went from being a huge importer of oil in 1973 to being more than self-sufficient in energy from 1997 onwards.

Denmark's first energy plan dates back to 1976. In the same year, the first step to accelerate wind power technology was taken with the launch of two national energy programmes within research and development, the energy research programme and the development programme on renewable energy. The primary focus of the two programmes was on wind energy. The development programme was closed down in 2002-03 whereas the research programme is still ongoing.

4.1.2 Taxes

Energy taxes on electricity and oil were introduced in Denmark in 1977 and are used to support R&D for renewable energy. Since then, the taxes have been increased several times and taxes have also been put on coal and natural gas.

In 1990, Denmark's third energy plan "Energy 2000 – an action plan for sustainable development" was introduced. This energy plan formulated the national objective of a 20% reduction in CO_2 emissions by 2005 compared to 1988 with a focus on savings in energy consumption, increased efficiency of the supply system, conversion to cleaner sources of energy and on research and development. In 1992, the taxes were therefore supplemented by CO_2 taxes. Today, the taxes are likewise used for promotion of energy savings and CO_2 reductions, also finance part of the state budget.

It is worth noting that the third energy plan in Denmark from 1990 was one of the first energy plans in the world without nuclear power. The energy plan instead set a target of wind power to cover 10% of the electricity demand in 2005. This target was reached already in 1999.

4.1.3 Financial support

Wind turbine generated electricity has been receiving support since 1976. In 1979, the Danish government began to subsidise parts of the investment costs of wind power projects. The programme was active up until 1989, and at its peak the subsidy was as high as 30% of the investment cost. It was discontinued however, as it began to receive criticism for special treatment of wind projects.

Up until 1992, the payment for the electricity produced by wind turbine as well as grid connection was agreed on between utilities, wind turbine manufacturers and wind turbine owners. However, in 1992, this voluntary agreement broke down. Instead, the government took action and introduced a fixed feed-in tariff and divided the cost of grid connection between utilities and wind turbine owners. The price paid for electricity generated from wind turbines was set at 85% of the utilities production and distribution cost.

The fixed feed-in tariff for wind power gave a stable and sound incentive for private investments and became a primary driver for the industry. Through feed-in tariffs, wind power plants were guaranteed a fixed price per kWh delivered to the grid. Fixed feed-in-tariffs have the downside of making wind power producers unresponsive to demand fluctuations and price signals in the market, thus potentially leading to inefficient resource allocation.

In 1992, wind power as well as electricity production from other renewable energy sources was also given priority access to the grid, and power utilities were given an obligation to develop or enhance the overall electricity grid to connect wind turbines. Rules on technical requirements for wind turbines, grid connection and settlement of electricity price are today managed by Energinet.dk and the Danish Energy Agency. It is important to set such rules at the beginning of wind development as it becomes very costly later on.

In 1999, an electricity reform was undertaken with focus on liberalising the market and reducing the cost of support to renewable energy technologies. The support to renewable energy was thereby changed from state budget finances to a public service obligation, which added an extra cost to the electricity bill for consumers. The feed-in tariff system for wind power was at the same time reduced significantly.

The reduction in the tariff given to wind production meant that almost no wind turbines were installed in Denmark between 2004 and 2008. From 1993-2004, the Danish wind industry grew from 500 MW to over 3,000 MW installed, but by 2004 the wind power development stagnated and the period from 2004-08 only saw an installation of 129 MW of new wind power capacity in Denmark.

An energy agreement was made in 2008 under which the Danish government committed themselves to addressing climate change at minimum economic cost and without risking security of supply. The energy agreement included installation of two offshore wind farms. Similarly, the tariff for wind power was likewise changed. The wind industry wished to have the support in the first years of production for financial reasons. The feed-in tariff system was thereby reformed and feed-in-premiums replaced the fixed feed-in-tariffs received on top of the market price. Wind turbine producers would receive 25 øre/kWh for the first 22,000 full load hours on top of the market price and an additional 2.3 øre/kWh as balancing cost. For offshore wind farms a special tariff is received depending on the winning bid in the tendering process (see next section 4.3).

The change in support to wind power in 2008 quickly had a positive effect on the installation of onshore wind turbines. In 2009, 116 MW of onshore wind power capacity were installed. Today the feed-in tariff has been slightly changed again. This is further elaborated upon in section 4.3.

4.1.4 Planning framework for wind power

A key feature of the Danish wind turbine development is the planning procedures, which have both ensured installation of wind turbine and inclusion of relevant stakeholders.

At the start of the wind industry in Denmark, the initiatives to erect wind turbines came mainly from local citizens. In the early 1980s, local wind turbine cooperatives developed. They consisted of small communities or several families that jointly invested in a shared wind turbine. During the 1980s, tax incentives were in place for families if they generated power to their local community, hence, more and more wind turbine cooperatives were established. By 1996, there were around 2,100 wind turbine cooperatives throughout the country, and in 2001 their share of the wind turbines installed in Denmark was 86%.

In parallel to the establishment of local wind turbine cooperatives, the first agreement between the government and energy utilities to invest in wind power capacity was made in 1985, after nuclear power was turned down by the parliament. The agreement included the installation of 100 MW of wind power capacity. Several agreements have been made since then. For example, in 1996 obligations were given to power utilities to establish an additional 900 MW of wind turbine capacity between 1996-2005, and in 1998, obligations were given to power utilities to engage in large-scale offshore wind power. The latter subsequently resulted in the commissioning of 325 MW offshore wind power distributed in two large scale demonstration wind farms in 2002 and 2003.

To identify wind turbine sites for the utility quotas, the government established a committee in 1991, which resulted in the first organised siting map for wind turbines for the whole country. Since the 1980s wind resource mapping has been developed and included in wind power planning both at national and municipal level. A refined wind atlas for Denmark identifying national wind resources was published in 1999. The wind atlas is used in the planning process when assessing the wind resource potential in a given area and to assess identification of potential wind development zones in line with the strategic environmental framework or assessment studies. In addition, it provides wind speed predictions with known and traceable accuracy for developers and allows them to calculate the potential yield of the wind energy resources. Lastly, the wind atlas also provides input to long-term grid planning.

Starting in 1994, onshore wind turbine siting has been part of long-term municipality planning, and municipalities must thereby decide where, and to what extent, wind turbines can be installed. A further set of planning regulation for offshore wind farms was developed by 1997, and the DEA became the authority for planning and installation of wind turbines at sea. In addition to giving permits for projects, the DEA also carries out analyses of environmental impacts and planning of future offshore wind farms. Since 2004, offshore wind farms in Denmark have been put up for an international tendering process handled by the DEA. In parallel hereto, a rarely used open-door procedure for offshore wind has been in effect, based on onshore support levels.

The local support given to wind power at the start of the wind industry in Denmark has been difficult to maintain with the progression towards fewer jointly owned and relatively large wind turbines. Throughout the years it has been essential to have the backing of the local community to ensure continued development of wind power. Hence, in more recent years, new initiatives to secure local involvement have been taken. The Energy Policy Agreement from February 21st of 2008 stipulated that a range of new initiatives should be undertaken to promote local acceptance, including options to purchase shares of new wind power projects.

Along with a gradual reorganisation of the energy supply relying on increased use of renewable energy, energy policy has created the foundation for Denmark to set ambitious targets for the reduction of greenhouse gas emissions and for use of renewable energy. The most recent energy agreement from 2012 includes policy measures that will realise an additional 2 GW wind power before 2020. Included in the agreement is an additional 500 MW onshore wind (1,800 MW new capacity while 1,300 MW is expected to be decommissioned), two additional large offshore wind farms with a total capacity of 1,000 MW, 350 MW of nearshore wind power, and 50 MW of designated R&D-nearshore wind power. The current government's long-term target for Danish energy policy is to become independent from fossil fuels by 2050.

4.2 Overall regulation and policy framework in Denmark

4.2.1 Long term planning

As highlighted above, Denmark has a strong tradition of long-term planning in the energy area, with energy agreements often supported by a broad spectrum of political parties, thus ensuring a following of a stable and steady energy planning course, even when governments change.

Generally speaking, the central government determines the long-term goals and targets with input from leading experts from academia, consultants, and industry. When these targets and/or policy goals have been established, the government then determines what incentives, infrastructure, and legal and/or regulatory frameworks must be in place in order to meet the targets. This policy and framework should be long-term and guaranteed, thus reducing the risk premium for investors, and thereby the cost for government. At the same time, they should also be designed in such a fashion, that as circumstances change, adjustment of the policies are flexible in order to bring about RE development in a cost-effective manner.

One of the critical elements in the establishment of long-term goals, and determining what incentives should be used to realise them, is scenario analysis. Scenario analyses of the future energy system provide a useful tool for identifying policy measures and actions that are required to transform our energy systems in a sustainable direction. Scenario analyses can give an overview of the different possible actions to reach a target while also analysing the effect of policy instruments. Instead of only focusing on a single technology or instrument, a scenario gives insight to the correlation between different instruments and offers a holistic approach to understanding the possible development to reach a target.

Prominent energy related scenario work in Denmark includes the 2008-10 work carried out by the Danish Commission on Climate Change Policy, an independent panel of 10 scientific experts tasked with investigating how Denmark can become independent from fossil fuels. The Commission was established in response to the RE commitment made in Denmark in the 1990s and the political vision of a 100% renewable energy system formulated by the former Danish Prime Minister An-

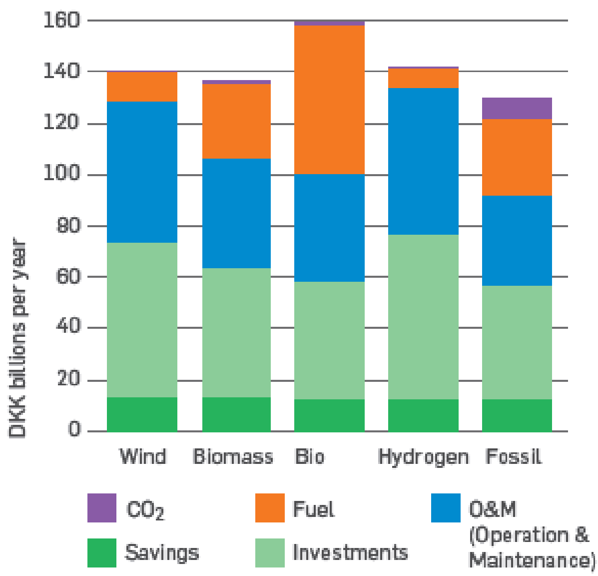

Figure 4-1: Distribution of total annual costs under 4 scenarios. Source: Tornbjerg, 2015, adapted from Danish Energy Agency, May 2014.

ders Fogh Rasmussen in 2006. The effort by the Danish Commission on Climate Change Policy laid the groundwork for the elaboration of Denmark's current strategy of attaining independence from fossil fuels by 2050.
The Danish Energy Agency is also active in undertaking scenario analysis, and presented in May 2014 scenario findings regarding the cost of realising a fossil fuel free society by 2050. The work described 4 potential RE scenarios, along with a scenario reliant on fossil fuels. The four RE scenarios varied according to their reliance on particular technologies (see Figure 4-1), and three of the four scenarios indicated costs that were only somewhat higher than that of the fossil fuel scenario.[4] The scenario that has gained the most momentum is the so-called wind scenario, and its development path is referred to in the political discussions of both the long term and short term policy actions.

The Danish TSO, Energinet.dk is also active in scenario analysis, though with a greater focus on system security, transmission capacity, grid development, and electricity and gas storage options. For the past number of years Energinet.dk has updated its analysis assumptions on an annual basis and presented them publicly. These public consultations thereby ensure a transport process, and provide an opportunity for Energinet.dk and interested parties to exchange knowledge. The scenario work by Energinet.dk is part of the work to ensure matching of the planning for the power and gas systems with the overall targets for the development of the sector. As such, both current and anticipated policies play an important role in defining the assumptions in the scenarios.

An example illustrating both the use of scenarios, and the interplay between various actors, is the discussion of a target of 50% wind in 2020. While not explicitly mentioned in the current Energy Agreement, the vision was an important factor in defining the desired wind buildout towards 2020. One of the studies first mentioning this target was first undertaken as a scenario analysis by Ea Energy Analyses, in cooperation with SEAS-NVE, on behalf of the Danish Wind Industry Association in 2007. The analysis investigated the possibility of supplying 50% of electricity from wind by 2025 as per the Government announced "visionary Danish energy policy" from January 2007. Somewhat controversial at the time, the scenario work contributed to shifting contemporary thinking, which questioned whether it was possible to integrate a 50% wind share in a responsible socio-economic manner. In the following years, some of the overall aspects the government had to undertake to realise this target, some of which also relied on scenario analysis, included:

- Establishing subsidies for onshore wind in order to encourage private investors to invest in wind production
- Developing bidding rounds for areas designated for offshore wind farms
- Ensuring that Energinet.dk undertook analysis and potential investments in both the domestic transmission grid and inter-connectors to neighbouring countries

4.2.2 Organisation of the Danish Energy Administration

The Ministry of Energy, Utilities and Climate ("MEUC") is organised around the minister's core staff ("Department") as shown in the figure below.

[4] The total costs did not costs/savings related to health care benefits, and it has been estimated that when these are included, then the RE scenarios are less expensive than the fossil fuel scenario.

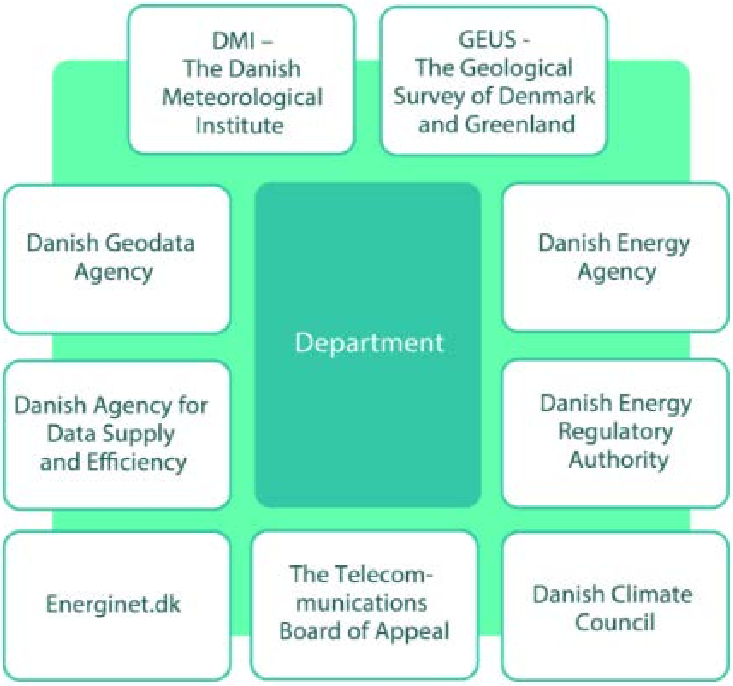

Figure 4-2: Agencies and institutions under the Danish Ministry of Energy, Utilities and Climate. source: www.efkm.dk/en

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4.3 Subsidy schemes for onshore and offshore wind power in Denmark today

4.3.1 Support to onshore wind turbines

Since 2008, electricity production from onshore wind turbines has received a feed-in-premium on top of the market price. The feed-in-premium system for onshore wind turbines was changed in connection with the energy agreement from 2012, a change that took effect on January 1st, 2014. The amendment introduced a ceiling on the sum of the market price and the feed-in-premium as well as changes to the calculation of full load hours that the turbine would receive support.

Hence, onshore wind turbines connected to the grid after January 1st, 2014 currently receive a feed-in premium of 25 øre/kWh (3.8 US c/kWh) with a ceiling equal to the market price + premium of 58 øre/kWh (8.7 US c/kWh). This means, if the market price of electricity is higher than 33 øre/kWh, the premium is reduced for every øre (1 øre = 0.15 US c) that the market price increases further. E.g. if the market price at a given time is 45 øre/kWh, the premium given on top of the market price is:

$$(Feed-in\ premium) - \left(Market\ price - 33\frac{øre}{kWh}\right) = 13\frac{øre}{kWh}$$

Since the year 2000, wind turbines have in addition to the feed-in premium received a balancing cost, which as of January 2016 is 1.8 øre/kWh for the first 20 years.

The feed-in premium given to onshore wind turbines connected after January 1st, 2014 is dependent on the effect of the turbine and rotor diameter. Support is given for the first 6,600 full load hours + rotor swept area in m^2 x 5.6 MWh/m^2. The change in calculation of the hours that the support is given to was undertaken to promote the most beneficial relation between nominal capacity and production.

Grid connection and reinforcement costs are to a large extent distributed among all electricity consumers. Thus, Denmark applies the concept of shallow connection cost for the investor. Only grid connection costs equivalent to connection to the nearest 10 kV station are allocated to the wind turbine owner independent from the real costs. Remaining costs for both grid connection and necessary reinforcements are shared among all electricity consumers in Denmark.

4.3.2 Support to offshore wind turbines

Offshore wind turbines under the open door scheme connected after February 2008 receive the same support as onshore wind power.

In the open-door procedure, the project developer takes the initiative to establish an offshore wind farm of a chosen size in a specific area. This is done by submitting an unsolicited application for a license to carry out preliminary investigations in the given area. The application must as a minimum include a description of the project, the anticipated scope of the preliminary investigations, the size and number of turbines, and the limits of the project's geographical siting. In an open-door project, the developer pays for the transmission of the produced electricity to land.

Special large offshore wind farms are supported in a separate scheme to onshore wind farms. Since 2004, offshore wind farms have been solicited via an open, two-stage tendering process. Since then, wind farms are commissioned under a competitive tender process and the electricity production cost is reflected via a feed-in tariff given per kWh produced for the first 50,000 full load hours.

A government tender is carried out to realise a political decision to establish a new offshore wind farm at the lowest possible cost. In the typical government tender procedure, the Danish Energy Agency announces a tender for an offshore wind turbine project of a specific size, e.g. 600 MW, within a specifically defined geographical area.

Depending on the nature of the project, the Danish Energy Agency invites applicants to submit a quotation for the price at which the bidders are willing to produce electricity in the form of a fixed feed-in tariff for a certain amount of produced electricity, calculated as number of full-load hours. The winning price will differ from project to project because the result of a tender depends on the project location, the wind conditions at the site, the competitive situation in the market at the time, etc. The areas for tender are the sites identified in the spatial planning process. The fact that other government authorities have been involved in the process of identifying sites for new offshore wind farms and have approved the final report, creates commitment to securing the sites. This, in turn, creates great investor security and up front knowledge about the sites.

The Danish independent transmission system operator (TSO) Energinet.dk is responsible for the Environmental Impact Assessment; geophysical surveys as well some geotechnical surveys to be carried out in the planning phase ahead of the call for tenders. These in-depth studies of the physical features of the site deepen the knowledge of the sites, and give future investors an insight into the technology choices they can take in the bidding procedure. This early action is implemented in order to reduce the length and uncertainty of the approval process and to give applicants better possibilities to offer a price that reflects the site specific costs. At the same time, it provides potential bidders with a high investment security and thus results in a reduced risk premium.

The results of the preliminary investigations for an offshore wind site are published in a timely manner before completion of the tendering procedure. The costs of the preliminary investigations will subsequently be refunded by the owner of the concession. Also, the costs will be published well before tenders for the wind farm are made. In projects covered by a government tender, Energinet.dk also finances, constructs, owns and maintains both the transformer station and the underwater cable that carries the electricity to land from the offshore wind farm.

In order to ensure rapid and un-bureaucratic application processing, enterprises or consortia awarded concession contracts utilise the Danish Energy Agency as their single point of access to assistance on issues related to all permitting. The Danish Energy Agency grants the required permits, and coordinates these with other relevant authorities. This means, the permits granted by the Danish Energy Agency also contain terms and conditions from other authorities, such as the Danish Nature Agency, the Danish Maritime Authority, the Danish Coastal Authority, the Danish Agency for Culture, the Ministry of Defence, etc.

The first call for tender was a result of the energy agreement from 2004, which included a call for tenders concerning two offshore wind farms of 200 MW each, with grid connection in 2007-08. Again in 2008 an energy agreement included a call for tenders with regard to an offshore wind farm of 400 MW for commission in 2013. The two most recent large offshore wind farms, Horn Rev 3 and Kriegers Flak, became a political decision as part of the energy agreement in 2012. Vattenfall won Horns Rev 3 and the wind farm is currently in erection. Vattenfall also won Kriegers flak in November 2016, and is expected to be fully operational in 2022.

The award criterion is price only, which helps ensure a fair and transparent procedure. The wind power developer awarded will thereby receive their winning bid as a guaranteed fixed price/kWh for 50,000 full load hours (approx. 12-15 years). Afterwards they receive only the spot market price. Note that no support is given in hours with a negative spot price, which Denmark typically experiences a few hours per year.

The winning bids for the five offshore wind farms in Denmark which have gone through a tendering process are shown in Table 4-1.

Offshore wind farm	Auction held	Size of wind farm	Winning bid nominal prices	Winning bid fixed 2016-prices
Horns Rev 2	Feb. 2005	209 MW (WT = 2.3 MW)	51.8 øre/kWh 8.6 US c/kWh	64 øre/kWh 9.6 US c/kWh
Rødsand 2	April 2008	207 MW (WT = 2.3 MW)	62.9 øre/kWh 12.3 US c/kWh	70.6 øre/kWh 10.6 US c/kWh
Anholt	April 2010	400 MW (WT = 3.6 MW)	105.1 øre/kWh 18.7 US c/kWh	113.6 øre/kWh 17 US c/kWh
Horns Rev 3	Feb 2015	400 MW *(WT = 8 MW)*	77 øre/kWh 11.4 US c/kWh	78.2 øre/kWh 11.7 US c/kWh
Kriegers Flak	Nov 2016	600 MW (WT > 8 MW)	37.2 øre/kWh 5.6 US c/kWh	37.2 øre/kWh 5.6 US c/kWh

Table 4-1: Winning bid of tendering process for five offshore wind farms in Denmark. The price is guaranteed for the first 50,000 full load hours and does not include the cost for transmission to shore, which is paid for by the transmission system operator and financed by tariffs on electricity.

4.3.3 Financing of the support schemes

Support for wind energy in Denmark is mainly funded by the Public Service Obligation (PSO) scheme. The PSO is paid by all consumers as part of the electricity bill and the funds are collected by retailers and transferred to the Danish TSO, Energinet.dk. Energinet.dk is thereby responsible for administration of the PSO. They are regulated by the *Act on Energinet.dk* and are monitored by the Danish Energy Regulatory Authority.

The PSO is not part of the government budget. However, to reduce the production cost at the Danish enterprises, they can get parts of their PSO costs covered through a subsidy scheme funded by the government budget. The PSO system was established 1999 and replaced financing on the government budget.

The PSO scheme is currently being revised and it is envisaged that there will be some future changes to how Denmark funds RE support schemes. The envisaged changes are a result of the European Commission critic of the PSO scheme, as the PSO scheme is imposed on all electricity consumers in Denmark, whether electricity production took place abroad or in Denmark, while the PSO only finances support schemes that foreign power generation do not have access to. Starting in 2017, the European Union requires support for RE is granted in a competitive bidding process on the basis of clear, transparent and non-discriminatory criteria. As a result, the current Danish PSO scheme will have to change. How Denmark will finance the support scheme for renewable energy in the future is yet unknown and a new finance model for support schemes is currently being discussed in parliament.

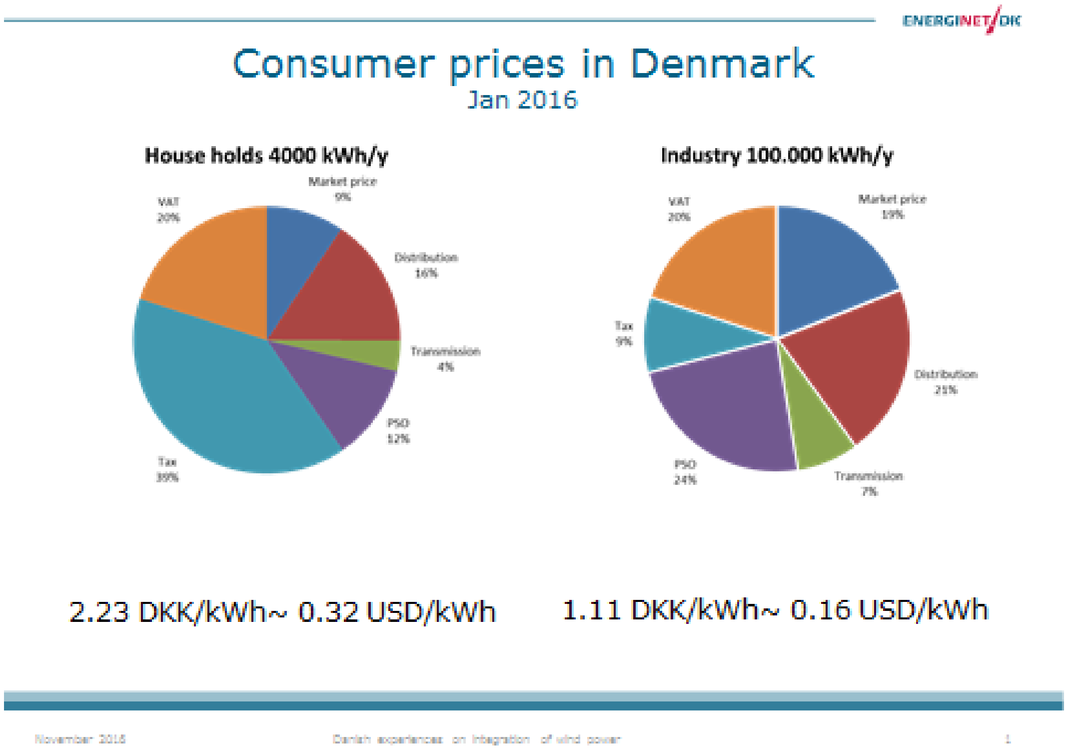

Figure 4-1: Breakdown of electricity prices in Denmark for households and SMEs.

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4.4 Discussion – looking into which subsidy schemes that are useful to kick start a development of wind power in Indonesia

The government of Indonesia has a target of supplying 23% of the primary energy mix with renewables by 2025, as set out in the National Energy Plan. According to the General Planning of National Electricity (RUKN), at least 25% of the fuel mix for power generation has to be renewable by 2025 in order to meet this target.[5] According to the RUKN, a total additional generation capacity of approximately 35 GW is needed by 2019 in order to meet the growing demand. Around 60-80% of the additional capacity is planned to be implemented via IPP.

According to current plans, the ambitious targets for renewable energy are mainly met by hydro and geothermal power. However, also other sources, such as wind and solar power can play a role in the future Indonesian power system. Wind power has the advantages of being an available natural resource, a very mature technology, and has short construction time compared to other technologies.

The Indonesian government has also set a target of increasing wind power capacity to 970 MW by 2025. It is expected that IPPs will develop the majority or all of the wind power plants in Indonesia to reach this target. Given IPP's crucial role in expanding the power capacity, hereunder the wind power capacity in Indonesia, the framework conditions must be close to perfect to ensure that developers and investors embark on this ambitious path.

Some of the barriers for achieving the wind power target in Indonesia are incomplete regulations as IPPs meet a number of technical and legal barriers. Two of the most pressing obstacles to IPP development concern acquiring the necessary permits and agreeing on a settlement price with PLN.

IPPs currently have to obtain permits from various governmental institutions before proceeding to project development in Indonesia. Important permits that must be obtained include for example a Business License (Izin Usaha), Approval of Environmental Impact Assessment (AMDAL), Location Permit (Izin Lokasi), Electricity Business License (IUPTL), etc. Acquiring these permits can be a long and cumbersome procedure as it is necessary to contact several governmental departments and ministries. In order to attract investors it is important to reduce the number, complexity and duration process of permits. As mentioned in section 4.3, one method used in Denmark for offshore wind farms is to establish one single point of access in charge of issuing all the permits needed for developing power projects. In Denmark, this institution is the Danish Energy Agency which thereby also issues permits from other governmental institutions. In Denmark this setup has ensured a rapid and uncomplicated application procedure and allowed IPPs to focus on price only.

Similarly, it can be considered to have e.g. the EIA study conducted prior to awarding a licence to build.

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[5] In order to calculate the fuel mix, renewable generation from geothermal power, hydro, wind and solar power are assumed to have an efficiency of 25%. In Denmark and Europe, renewable targets for power generation are usually stated as percentages of power generation (or power consumption), which does not require any assumption on the efficiency for e.g. wind and solar.

Agreeing on a settlement price for power production between the IPP and PLN is a complicated process as PLN seems restricted in terms of the settlement price they can allow. With no established tariff mechanisms or guidance on incentives from MEMR, the negotiations between PLN and private developers are proceeding very slowly. At the time of writing, a ministerial decree of feed-in tariff for wind power has been drafted and is currently being discussed internally – the issuance of the new pricing regime for wind power would be a big step towards ensuring good framework conditions for IPPs. In this context, enhanced cooperation between MEMR and PLN is equally important and could serve to minimise some of the obstacles that IPPs are facing when pursuing development of wind power projects in Indonesia.

In Denmark and Europe, various subsidy schemes for both wind power in particular, and renewable energy in general, have been tested. From a theoretical point of view, indirect support to renewable energy by taxing CO_2 emissions can be the preferred option if CO_2 emissions are the main concern. However, this setup requires the establishment of market prices for electricity. In addition, the European efforts on establishing a CO_2 quota scheme have proven difficult in terms of being the single incentive scheme for renewable energy. Therefore, in most European countries investments in renewable energy are driven by a combination of a CO_2 taxes (or obligation to acquire quotas in a quota market), and direct support for renewables. A brief overview on advantages and disadvantages for different schemes is given in Table 4-2:

- Lump-sum payment to investors. A lump-sum payment is independent of actual RES-E generation. This payment lowers investment costs and makes investments in RES-E attractive, but it does not distort the price signal from the market during operation
- Premium feed-in tariffs: Provide premium payments (e.g. $/MWh) on top of market prices for electricity. Under this scheme RES-E generators have two sources of income: One from selling power directly on the electricity market and one from the feed-in premium
- Tradable green certificates: A tradable commodity proving that certain electricity is generated using RES-E. Typically one certificate represents generation of 1 MWh. The certificates can be traded separately from the energy produced. Several countries (e.g. Sweden) use green certificates as a mean to make the support of green electricity generation closer to a market economy instead of more bureaucratic investment support and feed-in tariffs
- Fixed feed-in tariffs: The generator of RES-E is guaranteed a fixed price per MWh generated or fed into the power grid. This can also be implemented as a Contract for Difference, where the generator receives payment from the market and a variable premium to meet the agreed feed-in tariff
- All of the above mechanisms can be combined with an auction scheme where only selected RES-E generators benefit from the subsidies and the level of the subsidy is based on the prices indicated by the project developers in their offers during the auction process

	Strengths	Weaknesses
CO_2 Tax/ CO_2 quota	• Tax directly on the emission that is to be avoided • Price of CO_2 integrated in the electricity price seen by both generators and consumers • Technology neutral • Market driven price setting of indirect support level if implement as quota market • Encourage RES-E generators to react to market signals	• Has proven difficult to implement effectively in Europe • Exposure to market prices and therefore risks for investors • Hard to support emerging technologies
Lump sum payment	• Does not distort market price directly • Encourage RES-E generators to react to market signals	• Risk for policy makers to pay for generation, that is not yet supplied • Exposure to market prices and therefore risks for investors
Green certificates	• Market driven price setting of support level • Technology neutral	• Risk for investors due to uncertainty of future certificate price • Harder to support emerging technologies s
Fixed feed-in tariffs	• Limits the risks for investors also in emerging technologies • Facilitates the penetration of new players in the market • Can be flexibly designed to accommodate different policy objectives and adapt to changes • Long term investment security offered in fixed feed-in tariffs drives industrial development in RES-E technologies	• Costly when high deployment rates are achieved • Tariff setting and tariff adjustment process is challenging and complex • Generation is not exposed to electricity market prices
Feed-in premium	• Fixed premiums encourage RES-E generators to react to market signals • Sliding premiums or capped fixed premiums minimise the support cost • Limit risk for investors, especially when sliding premium or fixed premium with floor • Flexibility for different designs • Well suited for liberalized electricity markets	• Fixed premiums without floor create revenue risk for investors and higher policy costs • Premium setting and adjustment process is challenging and complex
Auction scheme	• High cost efficiency due to price competition • Useful to establish competitive pricing • High investor security if auctions are linked to long-term PPAs • Useful for volume and budget control • Well scheduled auctions can increase the predictability of new RES-E supply • Other policy objectives can be achieved through auctions	• Discontinuous market development (stop-and-go cycles) • Relatively high risks of not winning the project for high investment costs from bidders • High administrative cost • Underbidding and need for penalties

Table 4-2: overview on different setups for support schemes. A direct CO_2 tax and a CO_2 quota-scheme have some similar strength and weaknesses, but differ in the way CO_2 emissions are priced: Either the policy makers set a limit on total emissions or a price on the emission.

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5 Challenges related to integration of wind power

Generally speaking, due to the fluctuating and variable nature of wind, there are four main challenges associated with integrating wind power:

1. To ensure a suitable grid to transport wind energy to the consumption centres, including technical requirements for e.g. voltage stability and short-circuit power
2. To ensure the value of wind when it is very windy
3. To ensure sufficient production capacity when there is no wind. Wind power expansion results in it being less attractive to build base load plants
4. To balance wind power production, i.e. managing wind's variability and forecasting challenges

5.1 Ensuring a suitable grid

A fundamental prerequisite for integration of wind power is a suitable grid, which is able to transport the power generation from wind turbines to load centres. Depending on the connection level, this concerns the grid at both distribution and transmission level. Therefore, grid planning and wind power planning need to be aligned.

Compared to conventional power plants, wind power resources can be further away from load centres, requiring a stronger grid over a longer distance. At the same time, generation is often more distributed, requiring a stronger grid at lower voltage levels. In addition, depending on the demand at distribution level, the distributed nature can reduce losses and flows. Finally, the variable nature of wind power generation can make it sensible to ensure a suitable transmission grid enabling the option to balance wind power generation over a large geographical area. This is strongly linked to ensuring the value of wind power in very wind conditions (see next section).

Grid considerations do not only address the transfer capacity, but also operational aspects for grid security. To some extent, these considerations can be addressed by requiring certain technical abilities from wind turbines by defining them in the grid code. In Denmark, municipalities are responsible for identifying areas for establishing wind turbines, and grid considerations can be a part of that process. See section 4.1. The grid codes are established by the transmission system operator. See section 9.2.

5.2 Ensuring the value of wind when it is very windy

If a large part of the produced wind power electricity is sold at low or negative prices the value of wind power is reduced. Depending on the regulatory framework, this can also directly affect the wind turbine's economy and thereby reduce the incentive to invest in new wind turbines. For this reason, it is crucial to ensure the value of wind, both to maintain its socio-economic value, and in order to preserve the economic foundation for continued wind power development. The solutions are to reduce production at other power production units, export to neighbouring countries, or to increase electricity consumption where this is economically attractive (increase demand response). Existing and new electricity consumption (electricity for heat generation, electric vehicles, etc.) can also assist by not using electricity during periods of the day when the electricity system is most hard-pressed.

When these options have been exhausted it would be possible to curtail production from some of the wind turbines, both for shorter periods consisting of a few minutes, or for longer periods extending several hours. This is possible for all modern wind turbines, but should be at last resort used only when system security is at stake, or when alternative measures are more expensive. As marginal generation cost on wind turbines are close to zero, curtailment will mean not using free power. Excess electricity is therefore not a technical problem, but rather an economic one, which can be minimised when the rest of the energy system is dynamic. In systems with very large shares of wind power, it will likely be economically beneficial to stop some wind turbines every now and then.

The value of wind is a subject of continuous discussion in Denmark, and can be a major driver when evaluating for example transmission projects.

5.3 Ensuring sufficient production capacity when it is not windy

As the share of wind in a power system rises, wind power will displace generation from conventional power plants, challenging their economy as the annual full load hours for these power plants are reduced. At the same time, sufficient power generation capacity is needed for times with low generation from wind power. These effects lead to a restructuring of the power sector with a greater need for peak load plants and less need for baseload plants. The Danish power system is in a process of going through this restructuring, and several thermal power plants have been closed down during recent years, not only due to the increasing wind share in Denmark, but also due to low electricity prices in general.

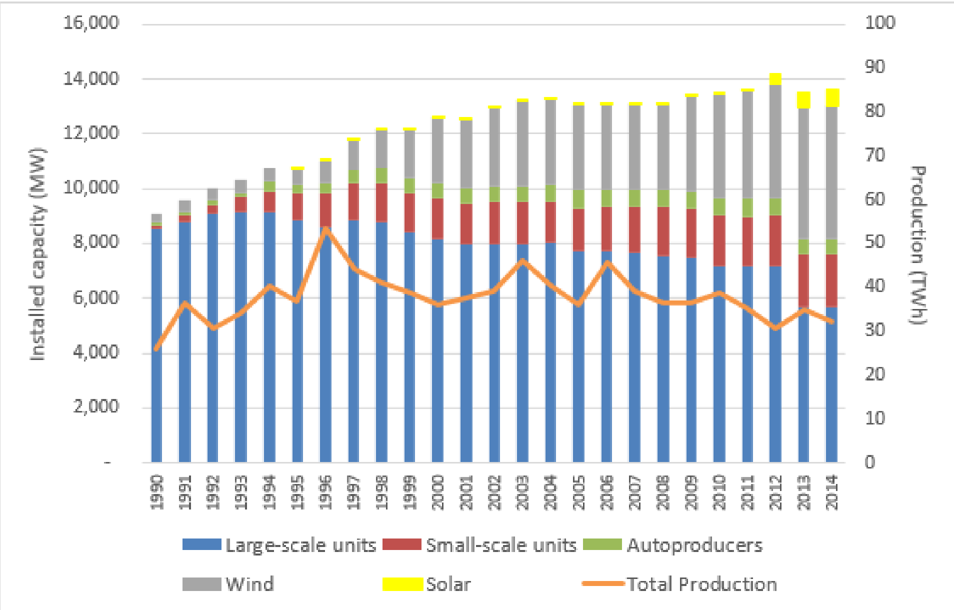


Figure 5-1: Development in installed power capacity in Denmark (left axis), and total production (right axis), 1990-2014 (Danish Energy Agency, 2015a)

The challenge of ensuring sufficient production capacity can be dealt with in several ways: Establishing peak generation capacity such as gas turbines, or via a closer integration of grid with neighbouring countries. Flexible electricity consumption and the activation of emergency power generators are also interesting possibilities that are, to a certain extent, already in use. The value of the various alternatives depends in particular upon the length of the duration that the strategy can be used. While certain types of flexible electricity consumption can only provide a solution for a number of hours with lacking capacity, other possibilities, such as peak load plants or international grid connections, can be used over longer periods of time with no wind power production, which potentially could last for a number of weeks.

In a well-functioning electricity market, power prices should provide incentive to ensure sufficient production capacity and an appropriate balance between peak and power plants. However, the transmission system operator Energinet.dk has the official responsibility for ensuring system adequacy and can acquire system reserves for this purpose (See chapter 7).

5.4 Balancing wind power

There is a need for balancing if e.g. the realised wind power production deviates from the forecasted generation as a result of altered wind conditions. As for conventional generators, other balancing needs due to production issues caused by technical problems or damage to the turbines will also need to be taken care of, but are typically less severe due to the distributed nature of wind generation capacity compared to fallouts from other (large) production units or transmission connections. Balancing can be achieved either by power plants or by consumers being prepared to change their production/consumption patterns with relatively short notice. Gas turbines can be well-suited to meet this need, but also coal-fired power plants and other productions units, electric boilers, or electrical heat pumps, and other consumption units can provide balancing services. Increased integration with neighbouring countries' energy systems can also provide access to more sources capable of providing balancing.

5.5 How wind power leads to the need for a more flexible power system

Overall, the above-mentioned challenges with integration of wind power lead to the need for a more flexible power system. Further details on flexibility options will be discussed in chapter 6.2.1 regarding the operational aspects and chapter 8 regarding the technological options. On the system level, duration curves for wind power, demand and residual load give a good illustration of the challenges. The Western Danish power system shows a high share of wind power of between 43% and 55% during the last 4 years (Table 5-1). This has a significant effect on the shape of the residual demand, which has to be served by other power generation, imports or handled by demand response. Wind power has a limited capacity credit (reduction of need for other capacity) of 2-11% in the actual years 2013-16, illustrated by a relatively high peak of the residual demand duration curve (Figure 5-2). Having wind turbines located over larger geographic areas will increase the capacity credit due to the smoothening effect of wind power. At the same time, the duration curve for residual demand shows fewer hours with relatively high demand (except peak demand) compared to the nominal demand curve. Furthermore, the number of hours with very low residual demand increases compared to the nominal demand, and the system also has to handle hours with negative residual demand. The steeper nature of the duration curve increases the need for a flexible system in order to be able to operate efficiently at both ends of the duration curve.

Table 5-1: Key numbers for wind generation and demand in Western Denmark. Numbers for 2016 are based on data for January till August

		2013	2014	2015	2016
Wind share	% of gross elec. demand	43%	51%	55%	47%
Peak wind generation	MWh/h	3,460	3,526	3,554	3,706
Peak demand	MWh/h	3,563	3,541	3,427	3,672
Peak residual demand	% of peak de-mand	98%	92%	98%	89%
Min residual demand	% of peak de-mand	-42%	-41%	-41%	-39%

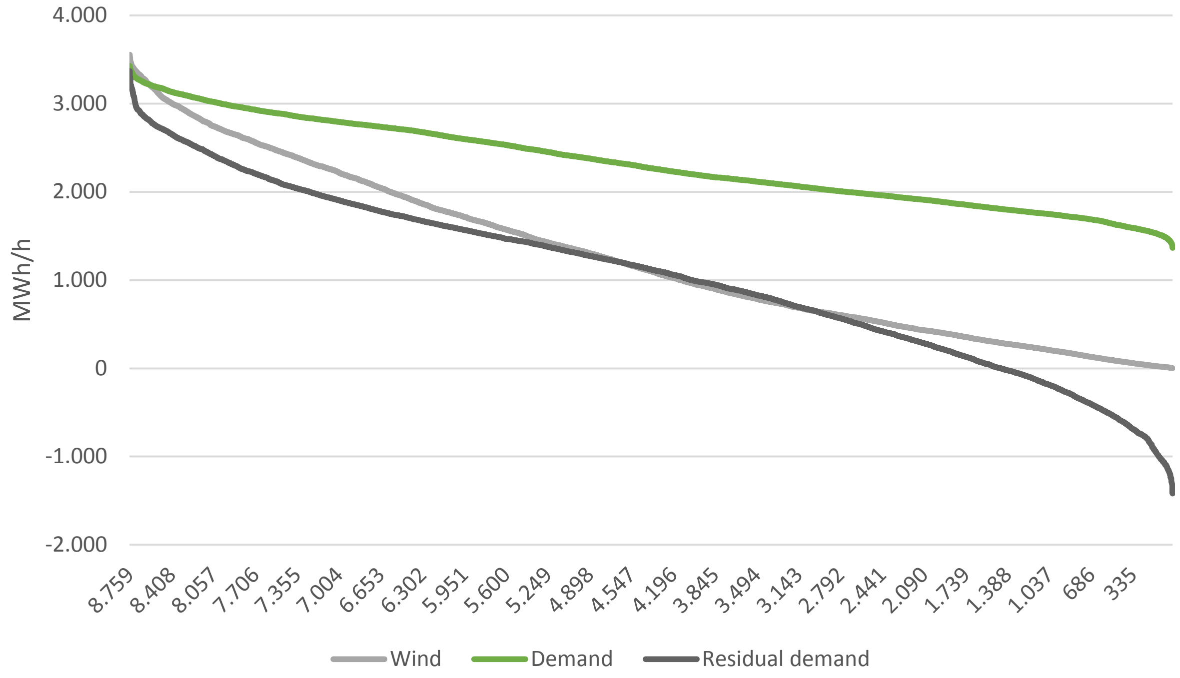


Figure 5-2: Duration curve for wind power and demand in Western Danish power system in 2015

Further flexibility requirements arise from increased changes of residual demand from hour-to-hour, and the challenges related to forecast errors. However, it is important to recognise that challenges related to the variability and forecast of wind power are significantly reduced if wind power is implemented across a larger geographical area. As an example, Figure 5-3 shows the correlation of variations in wind power generation depending on the distance. While the 12-hour average generation shows significant correlation also over a larger area, variations of the 5 or 30 minutes average generation variations are almost uncorrelated just 50 km apart. The effect is also apparent in Figure 5-4, showing generation variations of a single turbine, a group of turbines, and the aggregated generation in Germany over the same time period. Variations are significantly smaller over the larger region, reducing the overall integration challenge. Consequently, simply scaling the generation patterns of single or few wind turbines in a small geographical area cannot estimate the challenges related to wind power.

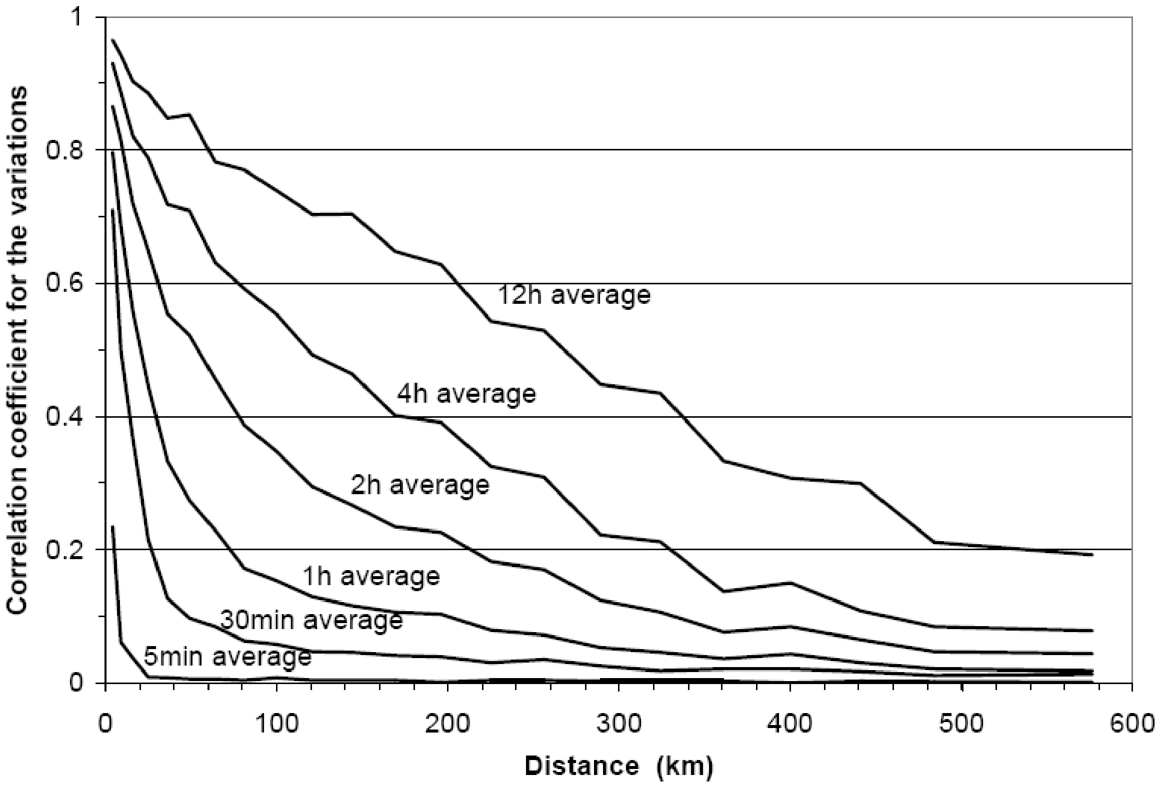


Figure 5-3: Correlation of wind power variations depending on distance between the generators. Source: IEA Wind.

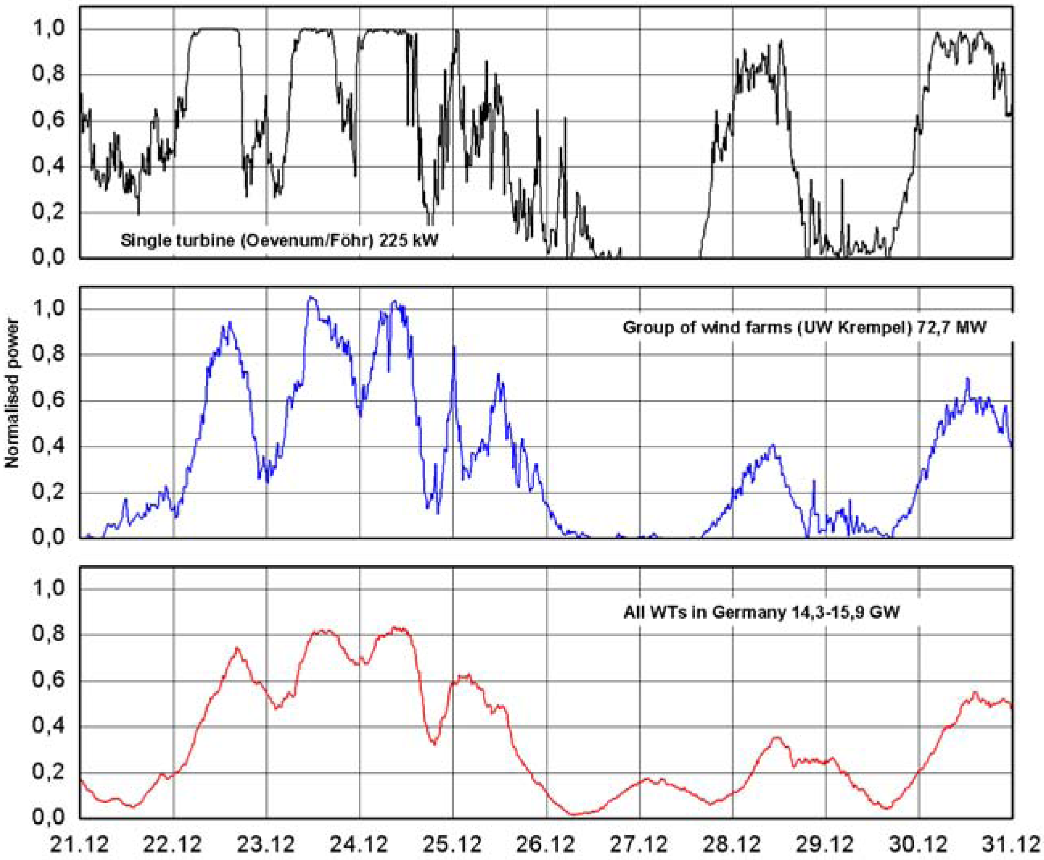


Figure 5-4: Variations of a single turbine, a wind farm, and aggregated generation over a larger area.

6 Power markets in Europe

The European electricity markets in general consist of a number of consecutive market places as illustrated in the following figure.

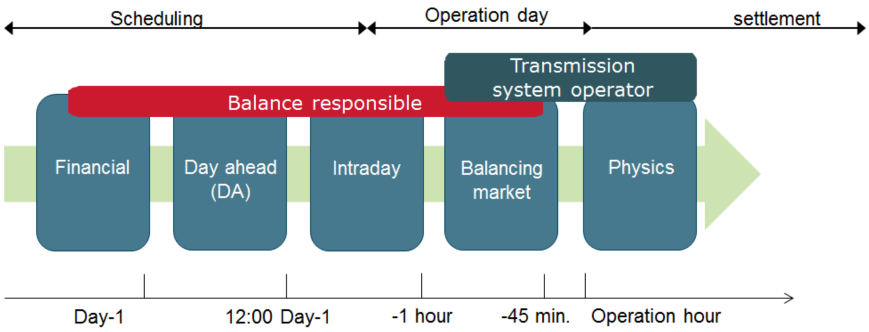


Figure 6-1: Main market places in the European electricity market.

The commercial market players have access to the financial markets as well as the day-ahead spot market, and the continuous trade intraday market. In the balancing market, the transmission system operator buys up and down regulation to ensure the physical system balance during the operation hour.

The financial markets are used for long-term price hedging only, and these markets are run by financial institutions independent of the system operators. In the Nordic countries, the major part of electricity is traded in the day-ahead spot market, where transmission capacity between price areas (MW) is allocated as an implicit part of the energy traded (MWh). Gate closure for the day-ahead spot market is 12:00. In the intraday market following the day-ahead market, the balance responsible parties can adjust their positions until 1 hour before the hour of operation. Typical reasons for adjusting the position of a balance responsible party are unplanned outages and changed forecasts for generation from variable renewable energy sources.

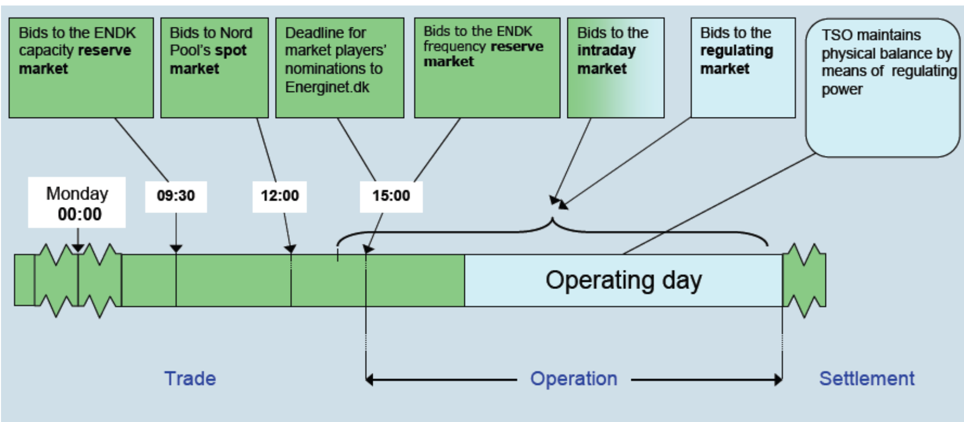


Figure 6-1: Successive markets for electricity in a Danish context (Source: Energinet.dk)

45 minutes before the hour of operation the system operator takes over the system to prepare the physical balancing with up and down regulation during the hour of operation. During this hour, the system operator

balances the physical system by activating bids for manual up and down regulation in order to reduce the residual imbalance for handling by the more expensive fast automatic regulation. In order to secure the availability of the needed resources for balancing, the transmission system operator operates different balancing markets, as outlined in Figure 6-1: Capacity reserves, frequency reserves and the regulating power market.

6.1 Price generation

Denmark is part of the Nordic power market, Nord Pool. In this market, there is an hourly market price for electricity (spot price) that reflects the marginal costs of generating electricity in the system. The market model is auction based; all electricity producers in an area receive the same price for their product at a certain time. Due to the auction principle, the producer has an incentive to bid into the market with prices based on their short-range marginal cost (SRMC). In order to cover fixed costs, producers are depending on the market clearing above their SRMC for a certain amount of hours per year.

Wind turbines would typically bid in at the lowest cost on the electricity market. This is due to the fact that wind power production does not involve any fuel costs. When the turbines are producing, they force the most expensive power plants out of the electricity market, thereby lowering the market price of electricity. In this way, wind power has a price lowering effect on the electricity market during periods of high wind levels. Large amounts of wind power production can also lead to hydroelectric plants withholding their production until a later time when electricity price levels are higher. This means, wind power can indirectly exert a price deflating effect even during periods when wind power production is low. As such, the amount of wind power generation today is just as important (or more important) for the price formation as the level of demand.

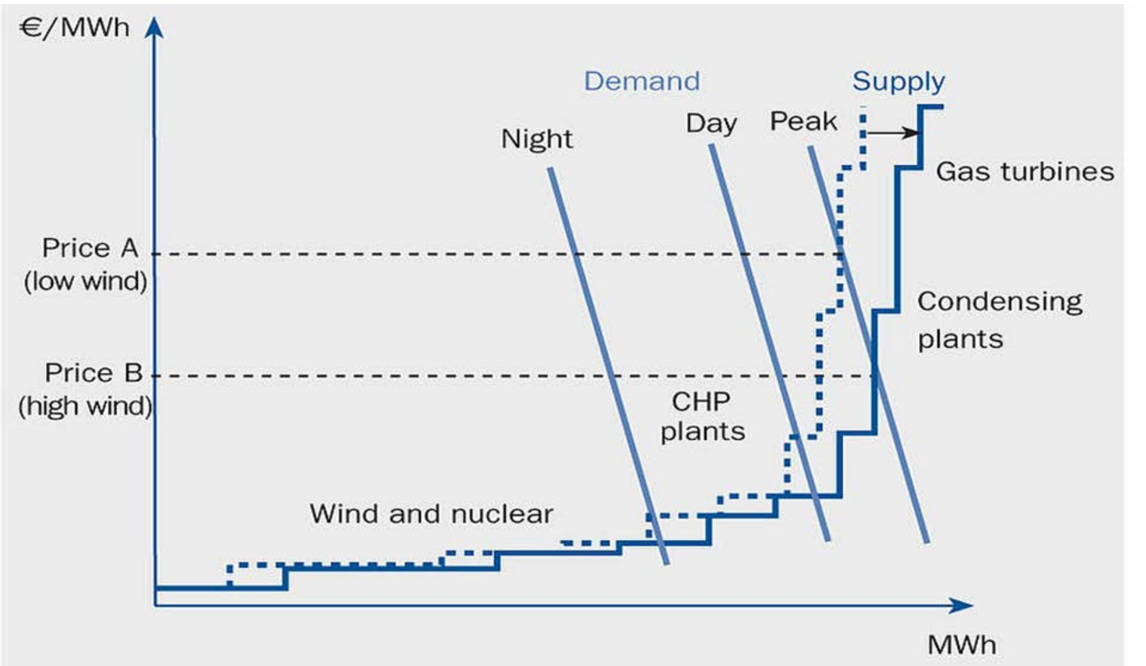


Figure 6-2: Price formation in the spot market – where bids for supply and demand meet. The dotted line shows a situation with low wind in the system and the solid-line a situation with high wind generation.

In a market-based system, the value of wind power will be expressed as the value that the market ascribes the production, directly expressed through the price of electricity. The price that the wind turbine can sell its production for in the market can be regarded as the socioeconomic value of wind turbine power production.[6]

6.1.1 Forward markets

The first markets that electricity can be purchased/sold on, are the forward or 'financial' markets. These commercial markets allow participants to buy or sell electricity to be delivered at a future time, and thereby lock in future prices today. These markets are referred to as financial markets as they do not require the participant to physically produce or utilise the electricity purchased/sold. Financial contracts manage risks and are essential for the market participants in the absence of long-term physical contractual markets. The figure below displays a screen shot of one these markets, the Nasdaq commodity market, where the market selected is 'Nordic electricity', the type is 'Year', and product is 'Futures', with the values being displayed in nominal euro per MWh/h.

PRODUCT SERIES	BID	ASK	LAST	+/-	%	HIGH	LOW	ON*	OFF*	VOL*	DAILY FIX	OI	SIZE**
ENOYR-17	19.21	19.25	19.20	-0.05	-0.26	19.35	19.20	81	81.0	162	19.20	9673	8760
ENOYR-18	18.90	18.95	18.95	0.05	0.26	19.10	18.90	53	33.0	86	18.95	4770	8760
ENOYR-19	18.55	18.65	18.55		0.00	18.66	18.55	11	31.0	42	18.55	2548	8760
ENOYR-20	20.12	20.20	20.10	0.09	0.45	20.10	20.10	2	2.0	4	20.10	964	8784

Figure 6-3: Screen shot from the Nasdaq commodity market, where the market selected is 'Nordic electricity', the type is 'Year', and product is 'Futures', with the values being displayed in nominal euro per MWh/h. (Nasdaq, 2016)

The red circle in the figure indicates the latest price that each of the 4 products was sold at, in this case end of year average electricity prices for 2017, 2018, 2019, and 2020. If we take 2020 as an example, at the time the screenshot was taken, it would be possible to purchase or sell 1 MWh of electricity for each hour during that year for an average price between 20.12-20.20 €/MWh/h, with the last trade occurring at a price of 20.10 €/MWh/h.

6.1.2 Reserve market

Moving to what are often referred to as the physical markets, and starting from the left in Figure 6-1, the TSO will accept bids on the reserve markets. Invitations for these bids are based on the TSOs expectation that it might require the ability to regulate within the hour of operation in the following day. Based on the TSOs anticipated potential demand for regulating power the following day, and the received bids, the TSO is in practice holding an auction for reserve capacity. This ensures the market participants (generators and consumers) not to enter market positions after the auction, whereby they are unable to participate in the spot market and the intraday market as described below. No energy is sold in the capacity reserve market, only the obligation to bid a certain amount of capacity into the regulating power market the following day,

[6] In a cost-benefit analysis the value of the sold production must be compared to the costs involved in erecting and maintaining the wind turbine.

and therefore participants winning the bids in the reserve market, must consider this obligation when bidding into the subsequent markets.

6.1.3 Day-Ahead Market

The day-ahead market was introduced briefly in section 6.1, as the central Nordic energy market is the spot market (Nord Pool Spot) where a daily competitive auction establishes a price for each hour of the next day. The trading horizon is 12-36 hours ahead and is done in the context of the next day's 24-hour period. The system price and the area prices are calculated after all participants' bids have been received before gate closure at 12:00. Participants' bids consist of price and an hourly volume in a certain bidding area. Retailers bid in with expected consumption, while the generators bid in with their production capacity and their associated production costs. Different types of bids exist, e.g. a bid for a specific hour or in block bids, which exist in several variations.

The price is determined as the intersection between the aggregated curves for demand and supply for each hour – taking the restriction imposed by transmission lines into account. Figure 6-4 illustrates the formation of the system price on the spot market as a price intersection between the purchase and sale of electricity.

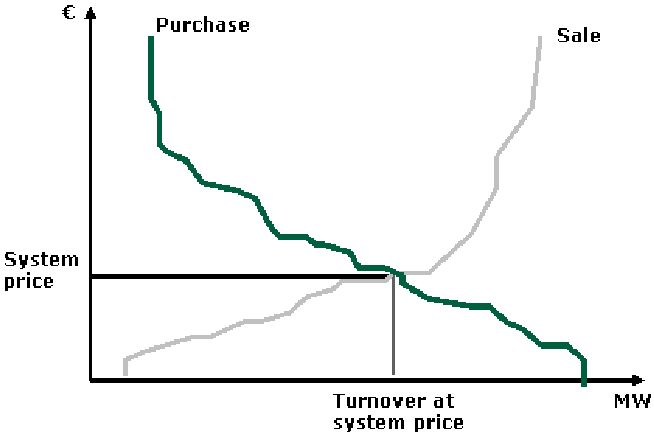


Figure 6-4: The formation of the system price for electricity on the Nord Pool Spot market (www.Nord Poolspot.com)

In common parlance, when one talks about the electricity price, one is referencing the day-ahead price, as this the price at which the vast majority of electricity is bought and sold at. In addition, the day-ahead price is also the reference price for the indexed financial contracts (as opposed to physical) used for hedging the power price longer term (as was discussed in the forward markets section above).

Sales bids could come from generation companies who own power generation facilities from conventional power stations, CHP-units, hydropower, wind farms, etc. Each generation company has its own view and knowledge of its short-run generation costs and therefore at which price it will be able to make a positive gain (or short-run operating profit). All generators (and consumers) receive (pay) the same price within the price area regardless of the bid price they have submitted. The power auction guarantees no requests to generate (consume) if the price is lower (higher) than the price you have bid. Therefore, each generator (and consumer) has the incentive to submit his true generation costs (willingness-to-pay) to the market, which means that the market ends up dispatching the generation with the lowest short-run costs and consumption with the highest value for consumers.

The deadline for bids to the day-ahead market is 12:00 CET for hourly bids for the 24 hours of the next day. This means, market participants are forced to make the best possible estimates concerning the costs and availability of their generation capacity for the next day. This is of course a challenge for wind power generators, which have to submit bids based on forecasts. If the forecasted wind does not appear at the time of operation, the wind generator will have sold power not able to produce, and will therefore be in what is referred to as 'imbalance'. Similarly, the availability of combined heat and power plants may be based on forecasted heat demand, and even conventional units may experience forced outages between the market clearing and the scheduled generation the next day. Retailers representing the consumers also have to bid based on the forecasted demand.

Generators and consumers that are not in balance with their positions (how much they have bought or sold) in the day-ahead market face an imbalance cost. This cost is based on the costs for the TSO to bring the system into balance in the regulating power market. To prevent this unfavourable imbalance cost, they may choose to engage in the intraday market.

The responsibility for maintaining the balance between what has been bought/sold and what is consumed/generated is held by the balance responsible parties (see text box).

Balance Responsible Parties (BRP) – There are roughly 40 registered BRPs in Denmark, and they can be divided into Load Balance Responsibles (LBR), Production Balance Responsibles (PBR) and Trade Responsibles.

- PBRs are by and large a power generation company, or several power generators joined together, but can also be aggregators that pool a number of smaller production units together. PBRs bid in on the various markets on behalf of their electricity producer(s)
- LBRs are typically electricity trading companies that through the pooling of consumers bid in on the various electricity markets. The main task of a LBR is to make a plan for the consumption the upcoming day. The load balance responsible must also document how the electricity has been purchased

In case of imbalances (deviations from the plan), the balance responsible must buy or sell this difference from the TSO, Energinet.dk.

Source: Energinet.dk (http://energinet.dk/EN/El/Engrosmarked/Aktoerer/Sider/Balanceansvarlige-aktoerer.aspx)

6.1.4 The Intraday Market (Elbas)

Given that the time from fixing of the price and the plans for demand and generation in the spot market to the actual delivery hours is up to 36 hours, deviations do occur. Deviations can stem from e.g. unforeseen changes in demand, tripping of generation or transmission lines, or from inaccurate prognoses for wind power generation. Such deviations can be mitigated during the operational day via entering into hourly contracts in the Elbas market, where electricity can be traded from the time the spot market closes up until 45 minutes before the operating hour.

Elbas is a continuous market, where the prices are set on a first-come-first-served basis, matching the highest priced purchase bid with the lowest priced supply bid. Balance responsible parties can use this market to rebalance their positions before the hour of operation. Smaller volumes are traded on Elbas than on the day-ahead market as the producers and consumers are only trading their expected deviations from what they have sold or bought. However, as the hour of operation approaches, market participants will get more knowledge of their physical positions, e.g. through newer forecasts and known forced outages. Through the continuous bilateral trading between the market participants, they are afforded the opportunity to re-balance their positions prior to the hour of operation.

6.1.5 Reserves

Electricity production and consumption always has to be in balance, and after the close of the Elbas market 45 minutes before the operating hour, the task of balancing the two is left to Energinet.dk. During the hour of operation, Energinet.dk utilises several types of reserves to ensure the stability of the system. The reserves can be grouped into automatic and manual reserves.

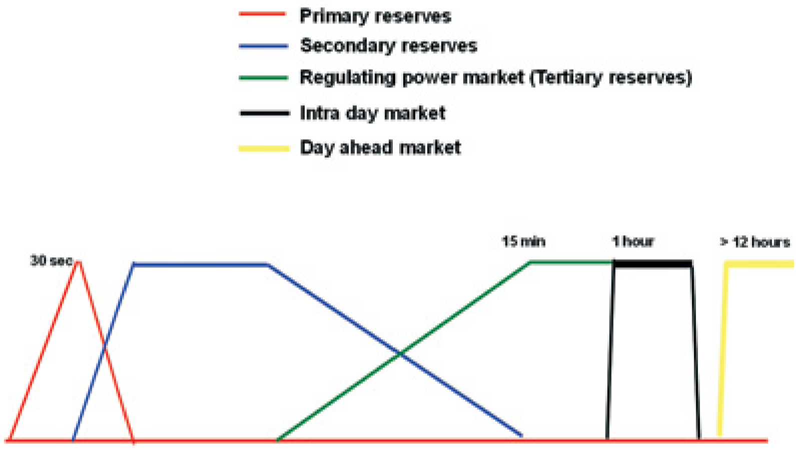


Figure 6-5: Timeframes and ramp rates for the various reserve types.

When there is an imbalance between the supply and demand in any power system, the frequency will move away from the desired operational frequency level (50 Hz). Automatically, frequency controlled primary reserves will adjust to compensate for the supply-demand imbalance. These reserves are purchased in the market and depending on the type, can receive both a reserve payment, and an energy payment if activated. As the name would indicate, they are activated automatically in accordance with frequency deviations, but are expensive and have limited capacity. Once these have been activated, they are quickly replaced by secondary and subsequently tertiary reserves, which are organised through the regulating power market.

The specification, purchase and settlement of reserves are described in further detail in section 7.4.

6.1.6 Regulating Power Market

To anticipate excessive use of automatic reserves and in order to re-establish their availability, regulating power is utilised. These tertiary reserves thereby allow for the other reserves to return from their maxed out state to be prepared for the next disturbance/imbalance which may occur. Regulating power is a manual reserve. In the Nordic region, it is defined as increased or decreased generation that can be fully activated within 15 minutes. Regulating power can also be demand that is increased or decreased. Activation can start at any time and the duration can vary.

In the Nordic countries there is a common regulating power market managed by the TSOs with a common merit order bidding list known as the NOIS-list (Nordic Operation Information List). The people responsible of the balance (for load or production) make bids consisting of amount (MW) and price (DKK/MWh). All bids for delivering regulating power are collected in the common NOIS list and are sorted by increasing prices for up-regulation (above spot price), and decreasing prices for down-regulation (below spot price). These bids can be submitted, adjusted, or removed until 45 minutes before the operational hour. In Denmark, the minimum bid size is 10 MW, and the maximum is 50 MW. The Elspot price meanwhile represents the minimum price for up regulating power bids and the maximum price for down regulating power bids.

An example of the NOIS-list is displayed below in Figure 6-6.

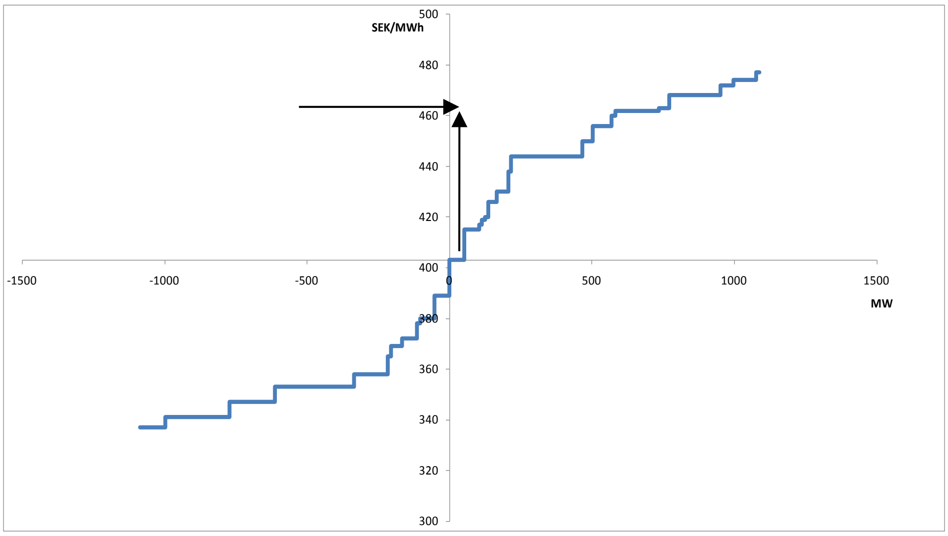


Figure 6-6: Example of the NOIS list, from 17.6.2009, CET 07-08. 583 MW of up regulating power was activated, corresponding to a price of 460 SEK/MWh (Data provided by SvK).

The bids are selected by the TSO based primarily on the price, but other things may be taken into consideration, such as the precise grid location of the regulating asset and any potential transmission congestions. The price for regulating power delivered within one hour is based on the highest accepted bid by the TSO within that hour for up regulation reserves (more generation), and the lowest accepted bid in that hour for down regulation reserves. As in the day-ahead market, this provides the incentive for market participants to bid their true short-run costs or willingness to consume, as they will receive the price established through competition.

The technologies participating in the regulating power market include both power generation and consumption technologies. Once a bid is activated by the TSO, the supplier must be able to fully adjust his generation or consumption within 15 minutes to the level dispatched by the TSO. This means that while the market is smaller than the day-ahead market in terms of the volumes transacted, the additional constraints preclude market participation by non-flexible technologies. Also, since the demand is driven by the imbalance, the price attained is usually more favourable than the spot market price, as can be seen from Figure 6-7.

Usually the generation units activated for up regulation have a higher short-run cost than the spot market price, or they would have been committed in the day-ahead market. For generators, down regulation provides an opportunity for units that have sold power in the day-ahead market, to avoid having to generate this power if the market imbalance is in surplus. Thereby the market participant can sell power at one price and buy that same power back at different price while earning a profit. This aspect rewards generators for providing flexibility to the system.

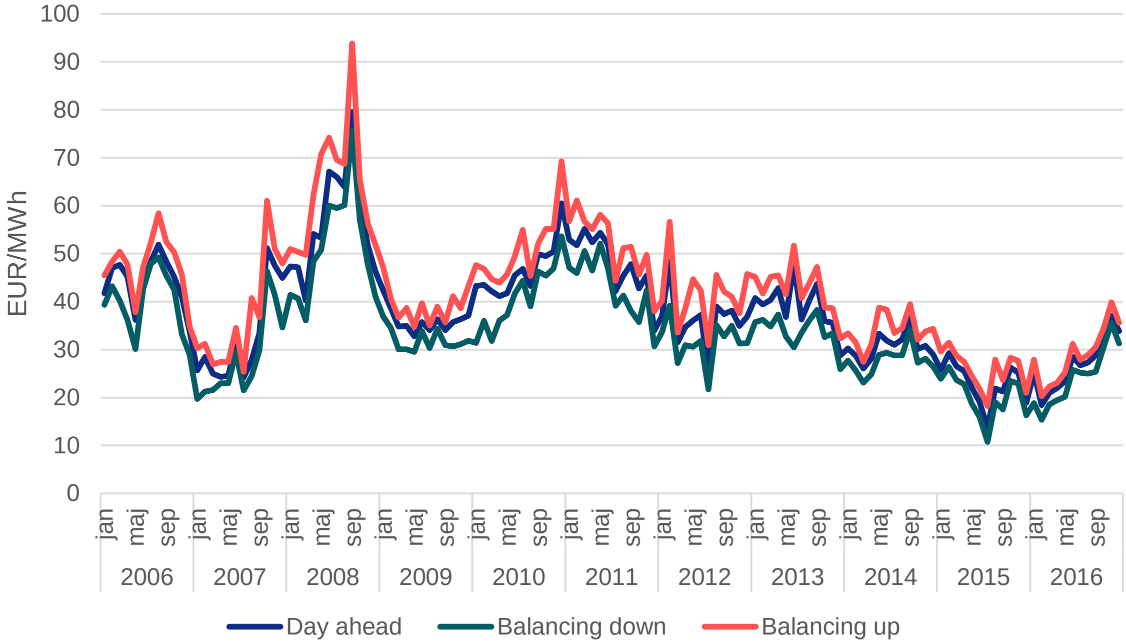


Figure 6-7: Typical relation between spot price in day-ahead market (blue) and balancing prices for up (red) and down (green). Prices shown as monthly averages for Western Denmark.

The converse holds for consuming technologies. If their consumption bid was not selected in the spot market, they may be activated in the down regulation market. Note that for consuming technologies, down regulation means increasing consumption. As these prices are more favourable for the purchaser of electricity as evidenced by Figure 6-7, there is an additional incentive here to be flexible and participate in reducing the system imbalances. Consuming technologies may also have been selected in the spot market, but then submit up regulation prices at which they are willing to decrease consumption in relation to their day-ahead position. Thereby, they effectively sell back power to the market and make a profit of the difference between the spot market and the up regulation price.

The costs for activating regulating power are allocated to the balance responsible parties causing the imbalances. For each balance responsible party, the imbalance is calculated as the difference between the submitted plan for generation/demand and actual measurements. On one hand this mechanism incentivises balance responsible parties to ensure the balance of their portfolios, and on the other hand the rather limited differences between spot and balancing prices demonstrate that costs for efficient balancing of a system with a rather high share of wind power are limited.

Naturally, some of the plants that are most capable of taking advantage of these market opportunities are plants which have a high degree of flexibility, both in terms of ability to regulation generation and consumption. Perhaps more importantly, they have the flexibility shift their energy supply needs between different technologies and the timing of energy supply. District heating plants in Denmark are especially well-suited towards providing this flexibility, and this will be detailed in the following chapter.

The down regulating price can sometimes be quite low, and even negative, thus indicating a large oversupply of electricity relative to the planned demand/supply balance. In these occurrences, producers that have planned to generate electricity can offer to reduce part or of all their production in the regulating power market. In essence, the producers are offering to 'buy' power by reducing their production. Plants with high stop/start costs would require a very low price for doing this, and therefore would require a large negative price in order to reduce their production. Wind farms on the other hand have very low start/stop costs, and they can therefore bid into the regulating power market with down regulation bids just below 0. I.e. they could offer to reduce their production by 10 MW for -10 DKK/MWh/h, and this 'bought' electricity which reduces the oversupply, 'costs' the wind plant -100 DKK/MWh/h, resulting in the wind park receiving a payment for reducing its production. In 2015, this active participation with down regulation via the regulating power market, equated to roughly 1.5% of total wind production on an annual basis according to estimates by Energinet.dk.

As mentioned on the foregoing page, the costs for activating regulating power are allocated to the balance responsible parties causing the imbalances. The price for balancing power is generally set according to the marginal price in the hourly market for regulating power, where the TSO buys manual up- and down-regulation. The pricing mechanism is illustrated in the below figure.

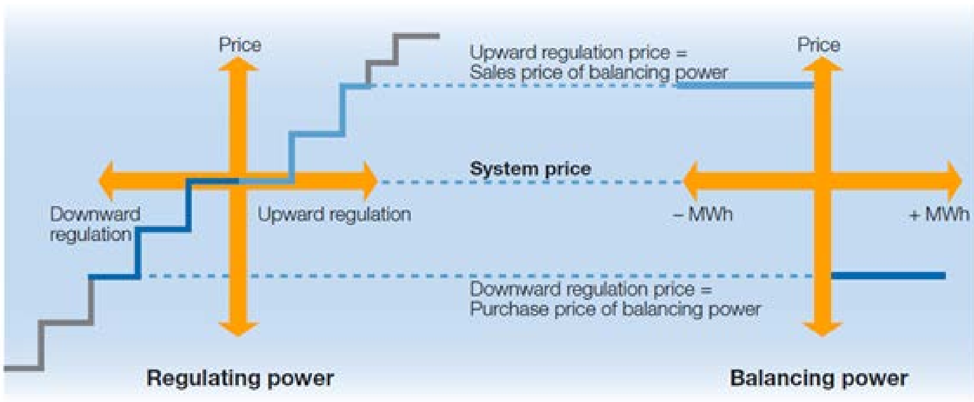


Figure 6-8: Market prices of up- and down regulating power

For demand balance responsible parties, the price for balancing power is always set to the marginal price for regulating power as illustrated above. For generation balance responsible parties, the price for balancing power is also set to the marginal price if the imbalance is in the same direction as the system imbalance, but for imbalances opposite the system imbalance - and thereby supporting the system - the price is set to the spot price.

The following figure illustrates the phases in the market planning and balance settlement process. In the market planning process all the balance responsible parties (BRPs) submit to the TSO schedules for their hourly generation, trade and demand portfolios. In the last hour before operation the TSO forecasts the expected system imbalances and prepares the physical balancing of the entire system by ordering regulating power (mFRR= manual Frequency Restoration Reserves). In the settlement phase the TSO costs for purchase of regulating power is allocated to the balance responsible parties according to their individual imbalances at balance prices.

All commercial trades in the day-ahead market (spot market) and the intraday market are settled according to the schedules independent of actual physical imbalances, which are handled and settled by the TSO.

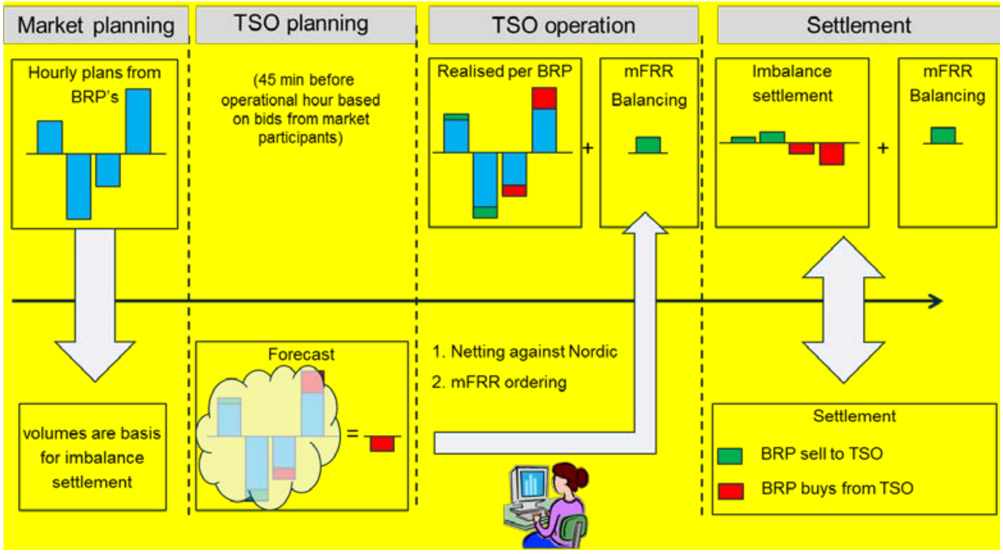


Figure 6-9 Settlement of imbalances takes place independent of spot market trade settlement

6.2 Discussion

Power markets are an important driver for operation of the power system in both a Danish and European context. In relation to integration of variable renewable energy sources, the role of electricity markets is primarily to ensure a dynamic merit order dispatch. It is important to realise that this can also be obtained with a central dispatch function as long as marginal generation costs are known for all generation units, and operation is not distorted by other incentives and contracts.

Within a merit order dispatch system, wind power and PV will always be dispatched first, and will in principle not need priority access to ensure economic dispatch due to the marginal costs of almost zero. However, maintaining an attractive investment climate for wind power is also an important consideration.

Apart from the principle behind a merit order dispatch, incentives need to be in place to ensure adjustment of the dispatch plans according to altered conditions, such as updated wind power forecasts. Again, while these incentives are primarily based on a market setup in Denmark, they can in principal also be implemented within a vertically integrated and operated power system. Important topics for further discussion within the Indonesian context include (see also section 8.6 for further comments on the actual power system operation):

- What are the current dispatch procedures in place today?
- What are the incentives for power generators within:
  - Flexible operation planning
  - Balancing power and adjustment of dispatch plans
  - Operational reserves

Incentives within the above-mentioned topics will be important in order to enable efficient integration of variable generation.

6.2.1 References

1. Ea (2015): The Danish Experience with Integrating Variable Renewable Energy. Study on behalf of Agora Energiewende

7 Operating the power system with wind power in Denmark

This chapter shares Danish experiences on balancing wind power in daily operations, looking into the specialised operational planning tools used in daily operations by the transmission system operator. Particular emphasis will be on forecasting of generation and demand. It will likewise discuss the capacity and reserve requirements of the Danish power system and how the integration of wind power has affected these requirements. At the end of the chapter, is an evaluation of the relevance of the Danish experiences in an Indonesian context, and possible means to overcome the challenges that the Indonesian power system experience will be discussed.

7.1 Wind power and system flexibility

Ensuring secure and efficient operation of an electricity system with large shares of variable wind power and PV requires a high degree of flexibility in both generation and transmission. In the future, flexibility in demand is also expected to contribute. In the Danish system, this flexibility is mainly obtained via very flexible power plants and exchange with neighbouring countries in the international electricity market. Conventional Danish coal-fired power plants are able to perform fast up and down regulation and stable operation at very low generation compared to rated output. Denmark is well interconnected to both the hydro-based electricity systems in the Nordic countries, and the thermal, nuclear, wind power and PV based systems on the European Continent.

In the following figures, the flexibility is illustrated with an example of dispatch for a week in September 2015 with an average wind power generation of 51% of Danish demand.

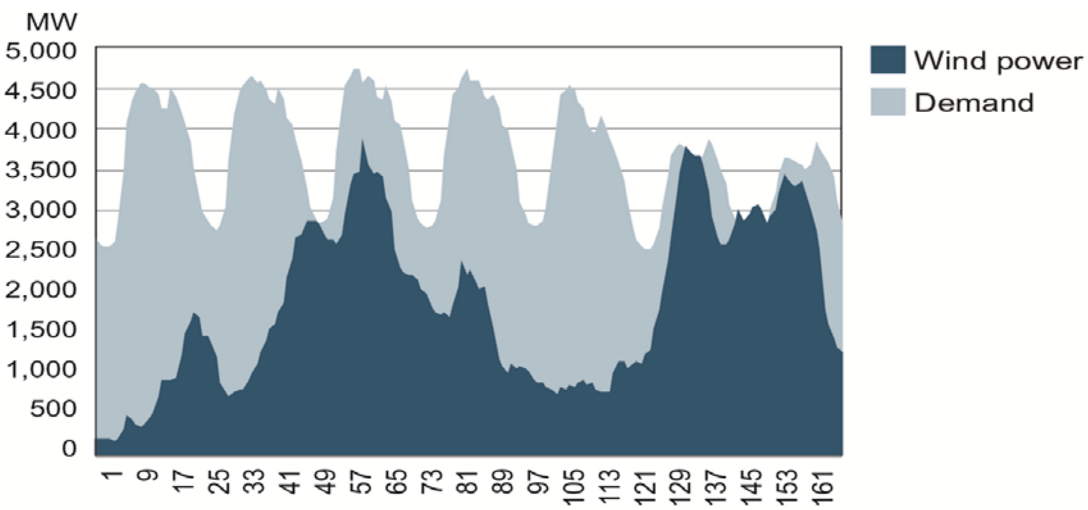


Figure 7-1: Demand and wind power generation for last week in September 2015 with wind power share 51% of demand.

During this week, wind power generation varies from almost none on Monday morning to exceeding demand during the weekend. It is obvious that a full utilisation of the wind power generation without curtailments requires a very dynamic response from the remaining system. In the next figure, the resulting dispatch balancing the Danish system is illustrated.

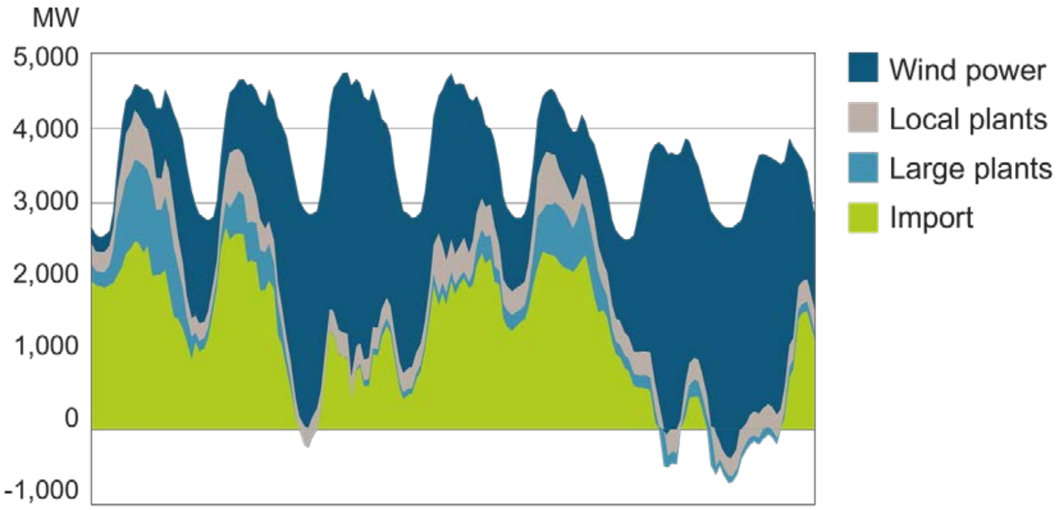


Figure 7-2: Resulting dispatch for last week in September 2015.

The top-curve illustrates the demand as in the previous figure, and the coloured areas illustrate the 4 sources for of electricity: Wind power, local plants, large plants and import. An area below "0" illustrates exports from Denmark. The high variability of the wind power is balanced via substantial variations in the generation from both local and large power plants, and in the exchange with neighbouring countries from imports to exports.

On Monday the wind power generation is very low, and the generation from power plants and import is high. Early on Wednesday morning the wind power generation almost covers the whole demand and the input from power plants is very limited. This morning is actually a historical day, in the sense that all large power plants in the Western part of Denmark were shut down, and in the Eastern part only 10 MW was generated via large plants. During these morning hours the demand in Denmark was covered by wind power with very limited input from power plants and net export. During the weekend it was very windy, and the wind power generation exceeded the demand in Denmark and the system was balanced via net export. But even in this situation with a very high wind power generation there was a major import from Germany, where wind power was also dominating in the Northern part of the country.

The following figure illustrates the resulting dispatch in further detail for the hour starting at 5 am Sunday morning. The map shows substantial transit from Germany through Denmark to the hydro dominated system in the Nordic countries. The hydro reservoirs in mainly Norway act as a "battery" for the Danish and German wind power, and the example illustrates the potential for balancing variable wind power by hydropower with reservoirs in combination with a flexible thermal generation system.

In the Danish case, the very dynamic dispatch is a result of the market clearing and not a central dispatch function. Only the final physical balancing of the two Danish market areas, Denmark West and East, is ensured with regulating power purchased by the system operator Energinet.dk in the regulating market as described in the previous section on electricity markets.

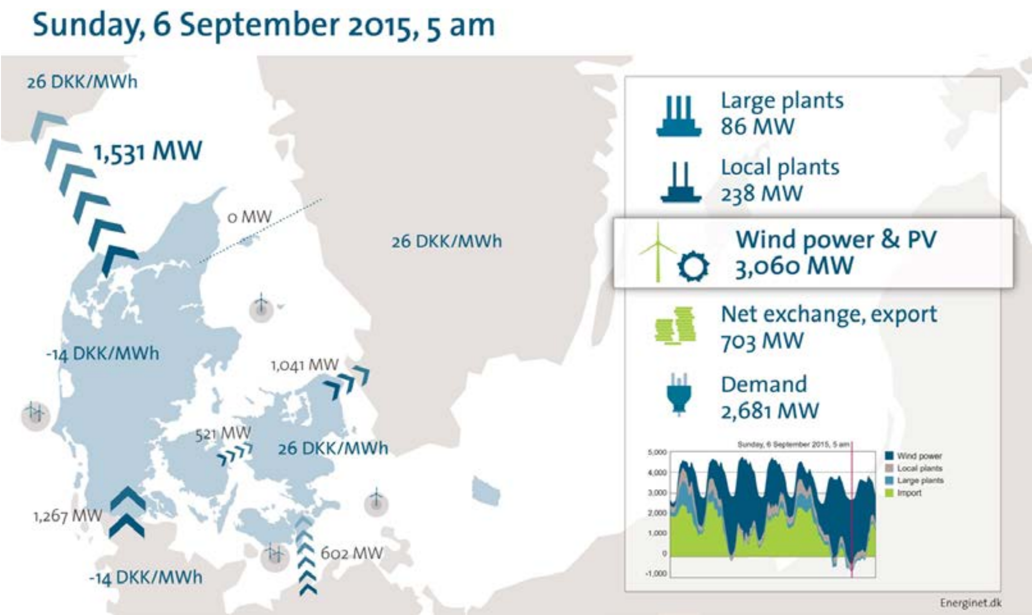


Figure 7-3 Resulting spot prices, generations and imports/exports Sunday, 6 September 2015, 5 am.

7.2 Operational planning

A key element in secure, and at the same time economically efficient, system operation with large shares of variable renewable energy sources is operational planning based on best available schedules and forecasts at all times. The importance of updated schedules and forecasts increases with growing shares of wind power and PV in the electricity system, and the following section provides a description of the procedures and tools implemented in Energinet.dk system operation.

In this context, the relevant operational planning starts 28 days before operation – designated as "D-28", and the following figure illustrates the main activities from D-28 to real time operation.

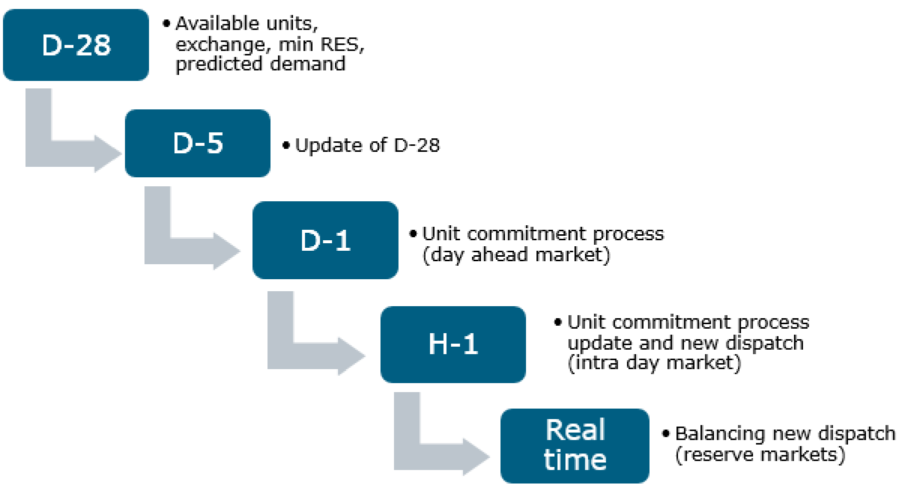


Figure 7-4: Main operational planning activities from D-28 to real time operation.

The operational planning process is initiated D-28 with a first estimate for the available generation units, expected exchange on interconnectors, minimum generation from RES and demand. This estimate is updated on D-5. The main result on D-1 is the unit commitment and dispatch resulting from the day-ahead market, and one hour before operation (H-1), the unit commitment and dispatch is updated according to the result of the intraday market, which closes at this time. During real time operation the system operator ensures the physical balance of the entire system via manual reserves in the balancing market and finally via automatic reserves.

Activities from D-1 to real time are described in further detail in the following sections.

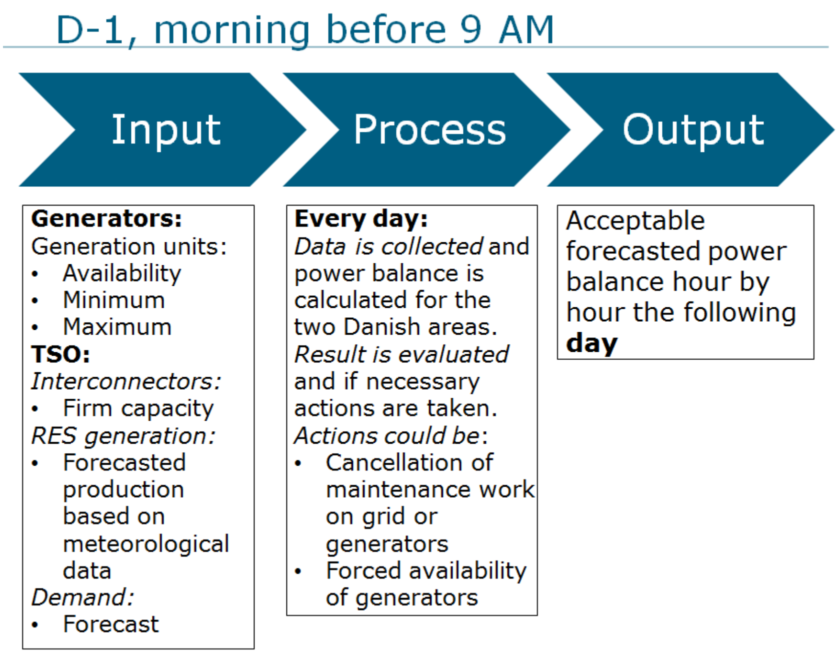


Figure 7-5: Process description for D-1, morning before 9 AM.

During the morning of D-1, updated information on generation, interconnectors, forecasts for RES and demand are collected, and the expected power balances for each hour are calculated. The results are evaluated, and to ensure acceptable capacity balances appropriate actions are taken. Possible actions could be cancellation of planned maintenance work on grid and generators and/or ordering forced availability of generators. The result of these processes is an acceptable power balance for each hour of the following day.

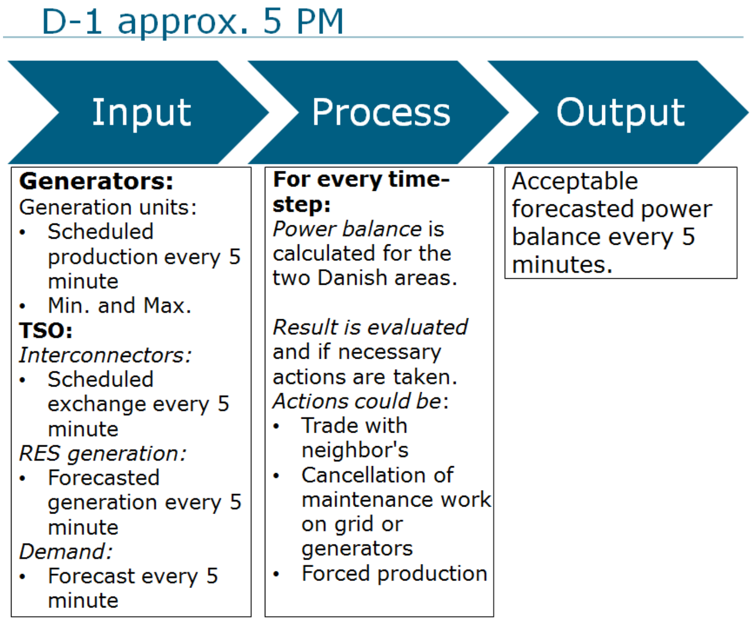


Figure 7-6: Process description for D-1, approximately 5 PM.

In the late afternoon of D-1, schedules and forecasts on 5 minute intervals are respectively collected and prepared. For every time-step the power balance is recalculated and evaluated. If necessary for obtaining acceptable power balances, actions such as trade with neighbouring areas, cancellation of planned maintenance works on grid and generators and/or ordering of forced operation of generation are under-taken. The result is now acceptable power balances on 5 minute time resolution.

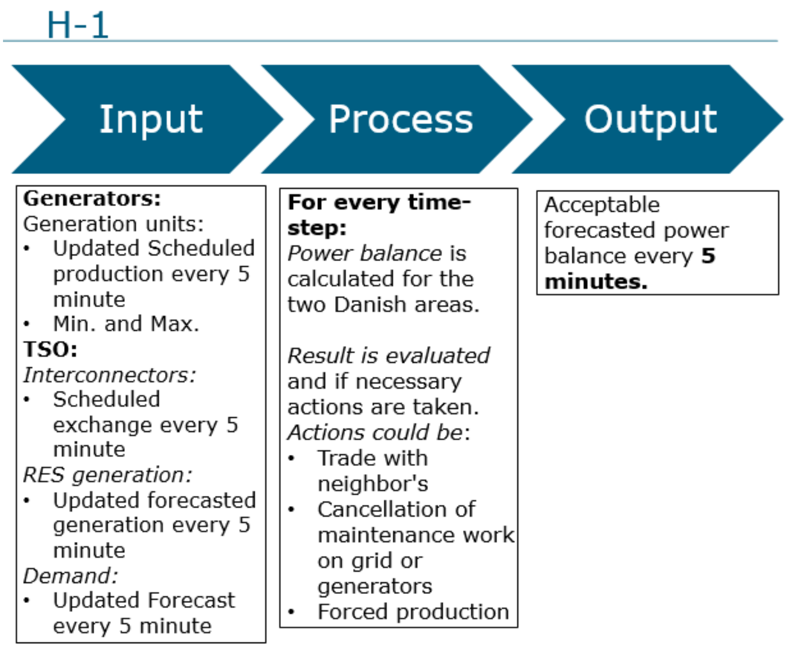


Figure 7-7: Process description for hour before operation H-1.

In the hour before operation, H-1, when the intraday market has closed, the 5 minute schedules are updated according to the results of the trades in the intraday market. The power balances are recalculated and re-evaluated. Necessary actions are taken to ensure acceptable forecasted power balances on 5 minute resolution.

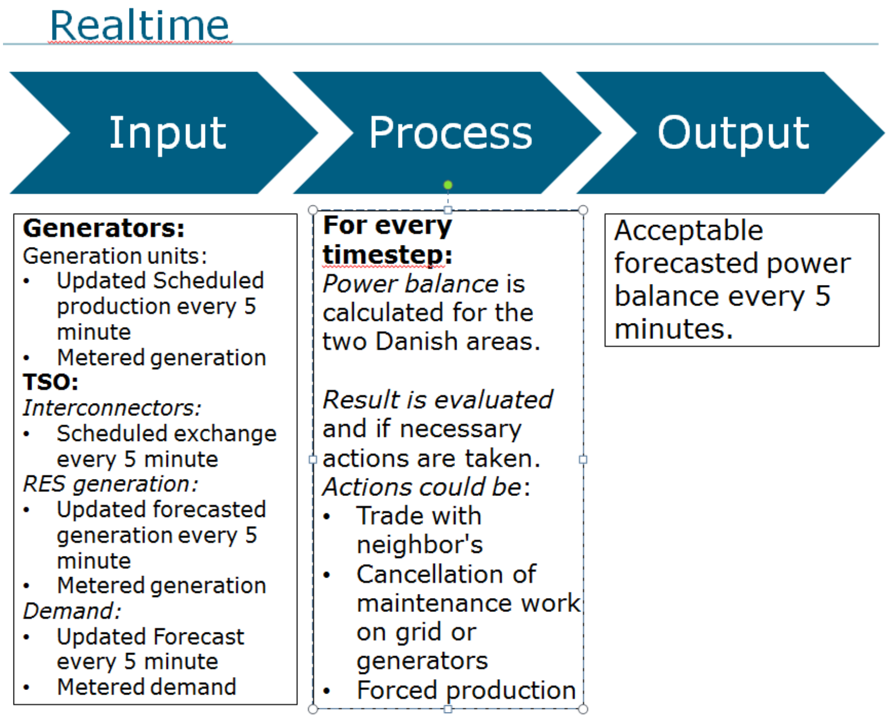


Figure 7-8: Process description for real time system operation.

During real time operation the 5 minute schedules and forecasts are continuously supplemented by on-line measurements on generation, RES and demand. The power balances are re-calculated and re-evaluated. Necessary actions are taken to ensure acceptable power balances in 5 minute resolution.

The basic idea with these procedures is to plan ahead and to base the planning on the best available data at any time. The target is to minimise the remaining imbalances to be handled with expensive automatic reserves by using cheaper manual reserves for anticipative balancing.

To support these operational planning procedures some tailor made IT-tools have been implemented in the control centre at Energinet.dk. An important system is the so-called Operational Planning System of which a screen dump is displayed in the following figure.

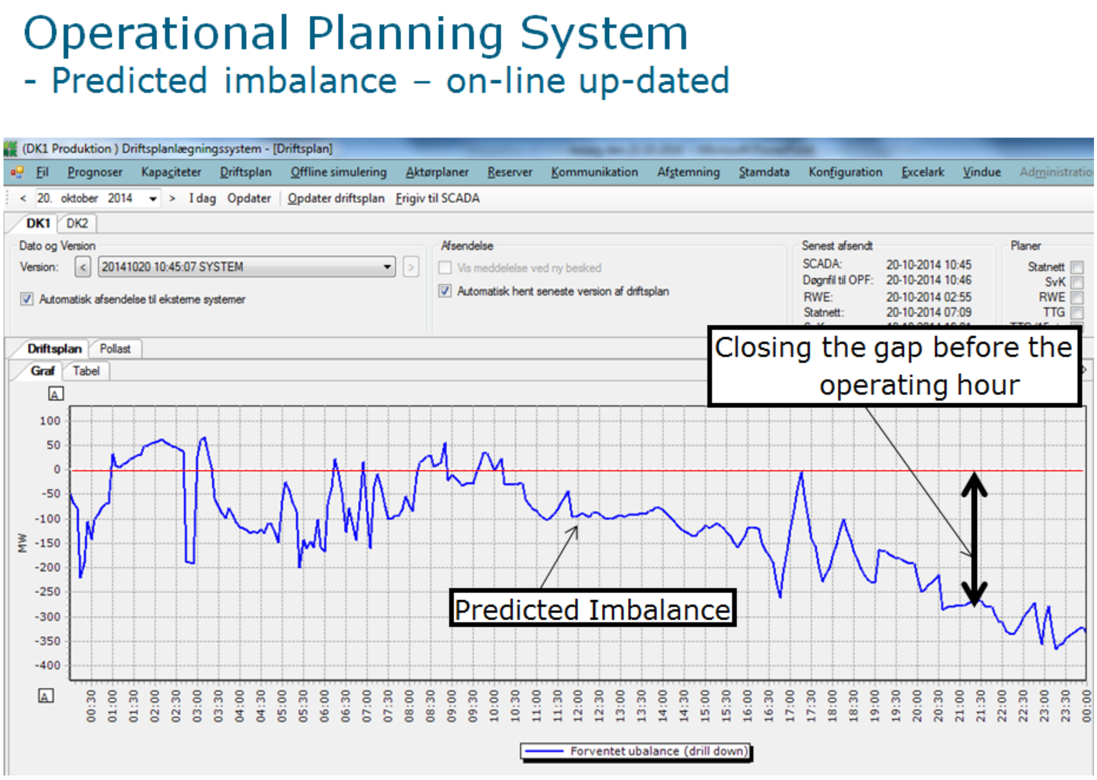


Figure 7-9: Screen dump from Energinet.dk's Operational Planning System. The graph shows the expected imbalances for the coming hours.

The Operational Planning System is used for collecting all continuously updated schedules and forecasts for generation, import/export and demand calculating the resulting predicted imbalance for the coming hours. The operator uses this system to evaluate the predicted imbalance and decide on activation of manual reserves for up and down regulation to close as much of the gap as possible before the operating hour.

By being prepared instead of surprised, the operator can run the electricity system more securely and economically efficient.

7.3 Forecasting systems

From the previous sections on electricity markets and system operation it is evident that precise forecasts for wind power are essential for the secure and efficient balancing of the Danish electricity system.

Wind power forecasting at Energinet.dk is divided into two categories:

- Offline
- Online

The offline forecasting is based on inputs from **N**umerical **W**eather **P**rediction (NWP) models, whereas the online forecast combines this information with scada data. Both categories are described below.

7.3.1 Offline Wind Power Forecasting

The current offline forecasting system running at Energinet.dk divides the country into 25 wind areas. The model calculates a wind power forecast for each of these areas based on information from a number of different NWP's.

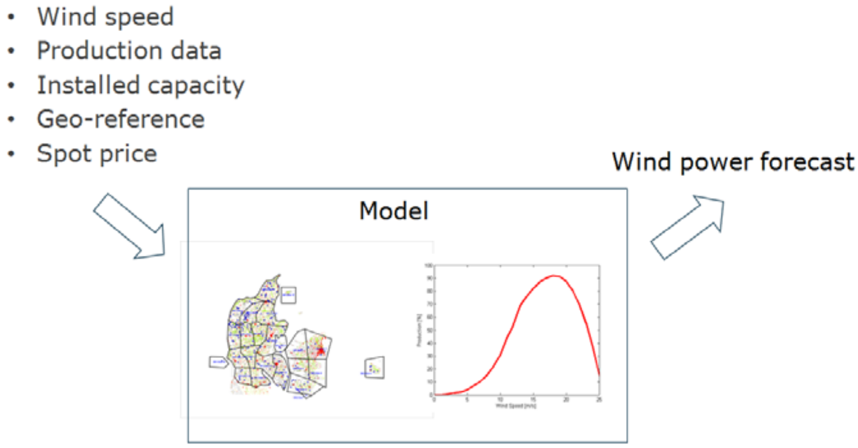


Figure 7-10: Offline wind power forecasting model

The offline forecasting system consists of two modules: *training* and *forecasting*. For each wind area the *training* module compares the historical average wind speed with the total historical production. Together with the installed capacity for each wind area, it is possible to calibrate a relative power curve (see Figure 7-11). This training is done on a daily basis using data from the last 3-6 months.

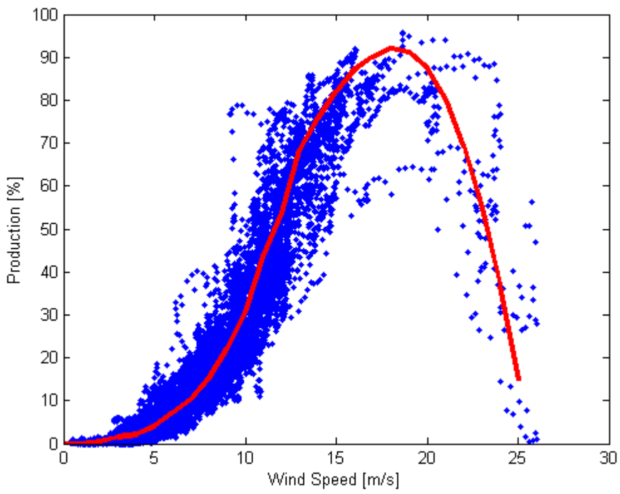


Figure 7-11: Relative power curve for wind power

Since wind power is a commercial product, some balance responsible parties choose to shut down their production if the price becomes too low. The training module thus ignores hours with prices below a given threshold when calculating the power curve. Instead it estimates a reduction coefficient for these hours, i.e. an estimate on how many turbines will be shut off.

Special attention is given to storms, i.e., hours when the turbines tend to cut off their production to protect the equipment. Storms are also included in the power curve, but retraining for storm wind speeds only takes place after a storm.

The described process is done for every NWP. In the end, it is necessary to calculate only one forecast. This is done by combining the output based on each NWP. The last step in the *training* module is thus to calculate the combination weights needed to obtain "the best" possible combination forecast.

The *forecasting* module converts a set of NWP's to wind power. New combination forecast output is calculated as soon as a new NWP becomes available. The module simply converts the wind speeds given in the NWP for each wind area to power, using the power curve and the latest master data (installed capacity for each wind area). Finally, the per NWP power output forecasts is then combined into a single forecast using the combination weights and summing over wind areas.

To make sure the forecast is well calibrated at all times, a monthly evaluation is undertaken. To keep it simple, focus is on the latest forecast available at 11:30 am (NP-spot deadline) covering the coming day. Only the total forecast for the two Danish price areas (DK1 and DK2) is evaluated. A typical mean absolute error is around 4.5% of installed capacity. In Figure 7-12, a typical error distribution is given for the two price areas. For comparison, the error distribution is also given for two single off shore wind parks. Clearly, it is relatively easier to forecast the total production from a well-distributed group of turbines as given in Denmark compared to forecasting one concentrated wind turbine park.

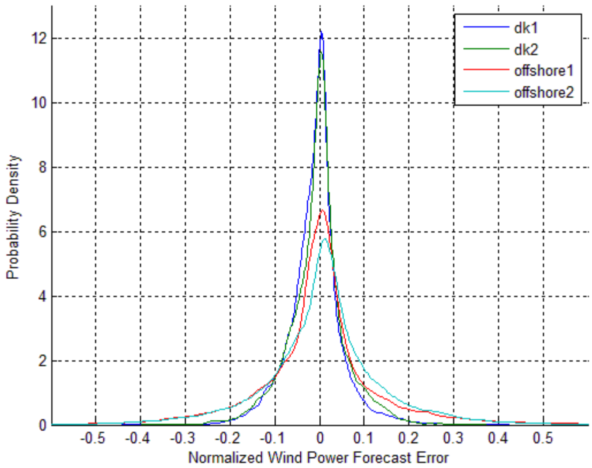


Figure 7-12: Normalized wind power forecast error

7.3.2 Online Wind Power Forecasting

Figure 7-13 displays the relative mean absolute error of the offline forecast as a function of forecast horizon. Notice the relative small improvement of looking 1 hour ahead compared to looking 40 hours ahead. It is possible to improve the performance significantly for the very short-term horizon (0-6 hours ahead) by using online measurements. This is the role of the online wind power forecast.

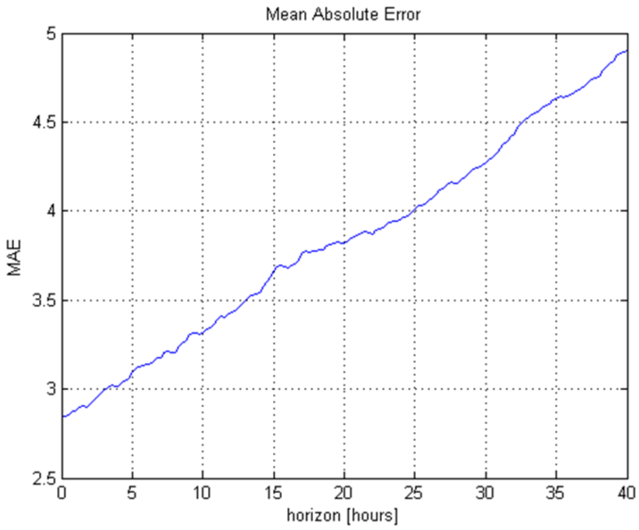


Figure 7-13: Mean absolute error in percent of installed capacity

The scada system provides an online estimate of the total production in each wind area. This estimate is updated every 5 minutes. Using these values, it is possible to estimate the current error of the offline forecast. The idea behind the online forecast is to try to forecast the future error of the offline forecast and thus obtain a way of calculating a corrected forecast – the online forecast.

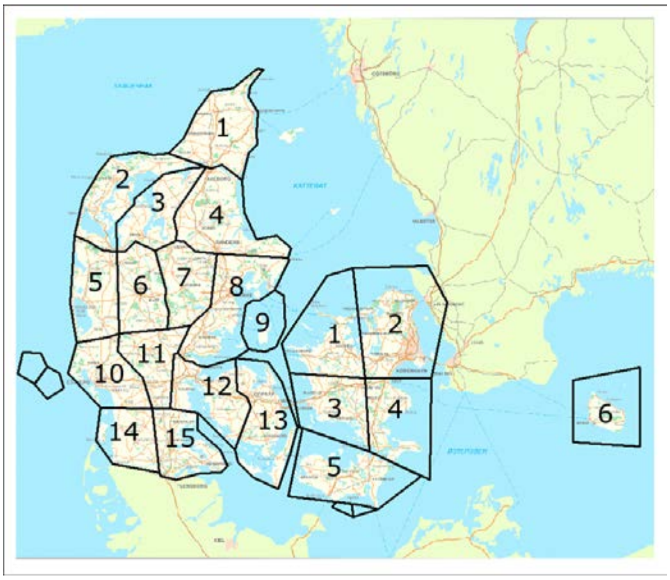


Figure 7-14 Defined wind areas in Denmark

Suppose a wind front is arriving earlier than expected. If the front is moving from west to east, the arrival of the front is first seen by the westerly wind areas as an increasing offline forecast error. If the model is correctly calibrated it is possible to use this information for the other wind areas, i.e., we expect a similar increase in the offline forecast errors for the other wind areas in the near future, as the front sweeps across the country.

This is the key idea behind the so-called spatiotemporal analysis, which is incorporated into the online wind power forecast.

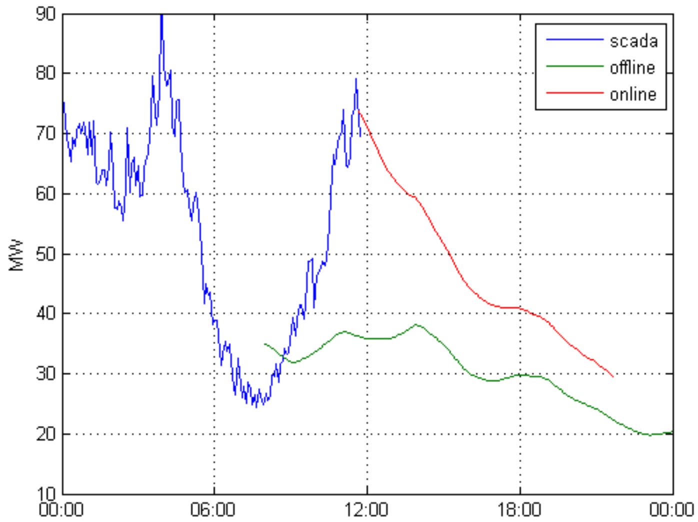


Figure 7-15: Comparison of offline and online forecasts.

The clear performance improvement using the spatiotemporal analysis is given in Figure 7-16.

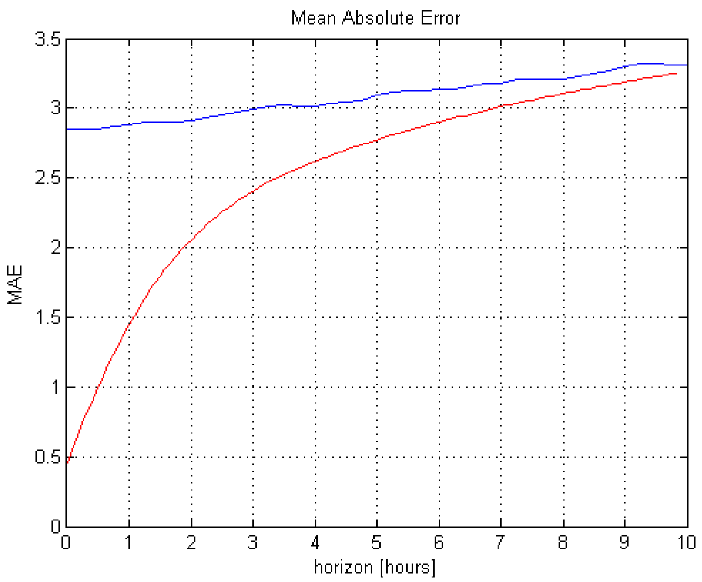
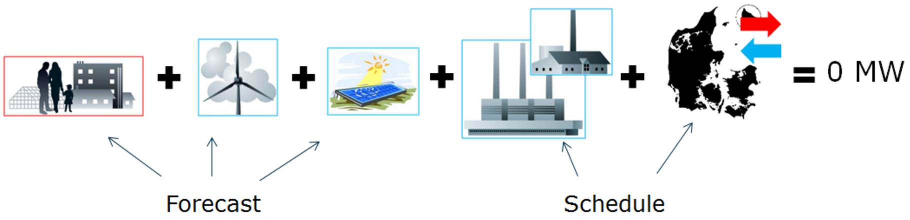


Figure 7-16: Performance improvements by using spatiotemporal analysis (red line).

Similar methods are used for solar power production and demand. Due to the small size of many PV plants, they are not obliged to supply online real time generation data to Energinet.dk. Instead, Energinet.dk acquires data from external data providers. Together with updated schedules for conventional production and exchange schedules for the interconnections, it is thus possible to foresee the imbalance in the coming hours quite precise.



All the forecasts and schedules are collected in Energinet.dk's operational planning system (DPS) and used to trade in the regulating power market. Figure 7-17 displays a screenshot of DPS showing wind power forecast output and scada data information. Similar displays exist for solar power, demand, power plants etc.

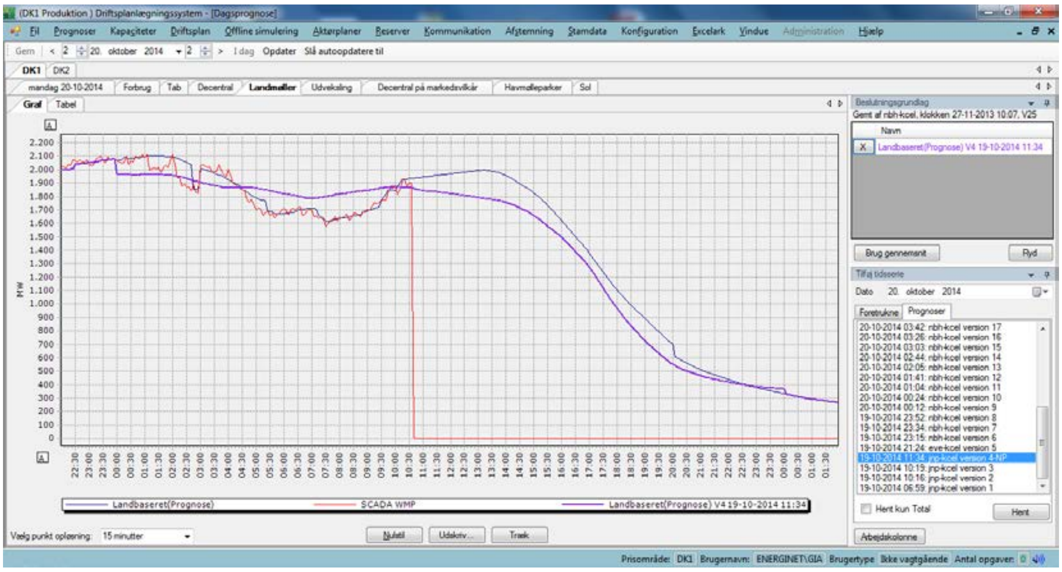


Figure 7-17: Screen dump from Operational Planning System showing wind power forecast output and scada data information. Day-ahead wind power forecast in purple, updated forecast in dark blue and actual wind power in red.

7.4 System reserve requirements

As described in section 2.2.2, the Danish power system is divided into two separate power systems, East and West, and the system reserve requirements differ slightly between the two areas. The following will concentrate on the Western price area DK1 (Jutland and Funen) synchronised with the continental European system.

The reserve requirements concern:

- Primary reserves
- Secondary/automatic reserves
- Tertiary/manual reserves

In addition to these ancillary services, Energinet.dk also ensures the availability of the necessary system services: Short-circuit power, reactive reserves, voltage control and dead-start ability.

Primary reserves

Procurement schema: Daily auction of blocks of 4 hours.
Remuneration schema: Marginal price per MW per hour. All accepted bids for up-and down-regulation receive an availability payment corresponding to the auction's marginal cost. Running the primary reserve is paid as ordinary imbalances.
Service provider: Generation or consumption units, which, by means of control equipment, respond to grid frequency deviations.
Ramp size/Speed drop: The reserve must at least be delivered linearly with frequency deviations between 20 and 200 MHz deviation. The first half of the activated reserve must be delivered within 15 seconds, while the last part must be delivered within 30 seconds at a frequency deviation +/- 200 MHz The regulation must continuously be active and contain features that ensure the maintenance of 100% power for a minimum of 15 minutes.
Minimum rated power: 0.3 MW.
Activation time/Duration: Automatically activated within 30 seconds. Maximum duration is 15 minutes.
Requirements: Primary regulation must be delivered at a frequency deviation of +/- 200 MHz compared to reference frequency of 50 Hz. This will usually mean in the range 49.8 to 50.2 Hz. It is allowed a dead band of +/- 20 MHz
Penalty clause: When it turns out that the capacity is not available, for example because of a breakdown, the availability payment is cancelled and the player must cover any additional costs for replacement. In case of accidents, which implies that a plant cannot supply reserve, the reserve must be re-established at one or more plants that can supply the reserve as soon as possible but within 30 minutes after the incident. If the supplier cannot re-establish the reserve, contact Energinet.dk within 15 minutes to announce where and when the reserve can be restored.

Secondary/automatic reserves

Procurement schema: Long term contract with Norway for delivery over the HVDC interconnector between Denmark and Norway. There is only ad hoc procurement in daily markets in DK1, when the availability of reserves from Norway is reduced.
Remuneration schema:

i. Capacity from Norway is remunerated through a fixed price. For the ad hoc procurement in daily markets the capacity is remunerated at Pay-as-bid price.
ii. Energy is remunerated marginally (DK1 spot price plus/less DKK 100/MWh, or at least, the price for upward/downward regulation at DK1)

Service provider: Secondary reserve regulation is automatic and provided by production or consumption units which, by means of control equipment, respond to signals received from Energinet.dk.
Cost recovery: This service is free of charge to users.
Minimum rated power: Minimum bid 1 MW, maximum bid 50 MW.

Penalty clause: When it turns out that the capacity is not available, for example because of a breakdown, the availability payment is cancelled and the player must cover any additional costs for replacement. In case of accidents, which implies that a plant cannot supply reserve, the reserve must be re-established at one or more plants that can supply the reserve as soon as possible but within 30 minutes after the incident. If the supplier cannot re-establish the reserve, contact Energinet.dk within 15 minutes to announce where and when the reserve can be restored.
Activation time/Duration: Automatically activated within 15 minutes.

Tertiary/manual reserves

Procurement schema: Daily auction, economic merit order. Energinet.dk buys manual reserve as upward regulation power. An auction is held once a day for each of the hours of the coming day of operation.
Remuneration schema: Capacity and energy are remunerated at hourly marginal prices.
Service provider: Typically gas turbines, thermal power, hydropower, CHP and load shedding. Wind power provides down-regulation.
Cost recovery: Reserve providers pay capacity fees and energy is paid by the imbalance parties through the imbalance settlement.
Minimum rated power: Minimum bid 10 MW. Maximum bid 50 MW.
Activation time/Duration: Manually activated within 15 min.
Penalty clause: When it turns out that the capacity is not available, for example because of a breakdown, the availability payment is cancelled and the player must cover any additional costs for replacement. In case of accidents, which implies that a plant cannot supply reserve, the reserve must be re-established at one or more plants that can supply the reserve as soon as possible but within 30 minutes after the incident. If the supplier cannot re-establish the reserve, contact Energinet.dk within 15 minutes to announce where and when the reserve can be restored.

Dimensioning of reserves

The reserve requirements in the Danish electricity system are designed to comply with the so-called "n-1" contingency criterion. According to this criterion the electricity system must be able to withstand the loss of one major component without interruptions in the continuous electricity supply. To comply with this an "n-1" redundancy is built into the system. In the Danish electricity system, the dimensioning fault is the loss of a major power plant or an interconnector of 700 MW. As a consequence of this requirement a tertiary/manual reserve of 700 MW is always ensured in the Danish electricity system.

As seen from the previous section on forecasting, it is possible to reduce the mean absolute error (MAE) to 1-2% of installed wind power capacity an hour before operation, when the intraday market closes and the system operator (Energinet.dk) takes over the physical balancing. With an installed wind power capacity of approximately 5 GW the MAE amounts to 50-100 MW, which is well within the reserves ensured to comply with the "n-1" criterion.

In the Danish electricity system, no extra reserves are ensured to handle uncertainties with respect to wind power. The dimensioning fault is still the loss of a power plant or an interconnector.

7.5 Discussion – How some of the power system's operational limitation and challenges that the Indonesian power system experience can be addressed in order to integrate more wind power

In addition to increased flexibility of the generation and power system, which is further discussed in chapter 8, development and implementation of advanced tools and procedures for operational planning in the control centres of the system operators will be crucial. Wind power and PV forecasting systems and the integration of these with scada and other operational planning systems should be given the highest possible priority. Danish experiences show that these tools are vital for a secure and efficient system operation without curtailment. Further points of discussion could include:

- What are the current planning procedures in the Indonesian power system, and what barriers and options for integration of wind power can be identified?
    - Planning horizons and procedures
    - System requirements for secure operation
    - Coordination between dispatch centres
- What are the requirements for regulating power?
- What are the requirements for other ancillary services?

8 Power system flexibility for integration of wind power in Denmark

This chapter will discuss the effects wind energy has on the power system and which flexibility measures are used in the Danish power system to contribute to the integration of wind power, such as interconnectors. The chapter will likewise touch upon Danish experiences with flexibility of conventional power plants as well as how to access the flexibility potential and possible solutions to reach an enhanced operational flexibility of power plants. Finally, the chapter will discuss possible measures that could be taken to increase the flexibility in the Indonesian power system.

8.1 The transmission system

The transmission system in both a national and international perspective plays an important role in ensuring the necessary flexibility in the Danish power system. Figure 8 displays a snapshot of the current Danish power system for a day in June, including the interconnections with Norway, Sweden and Germany.

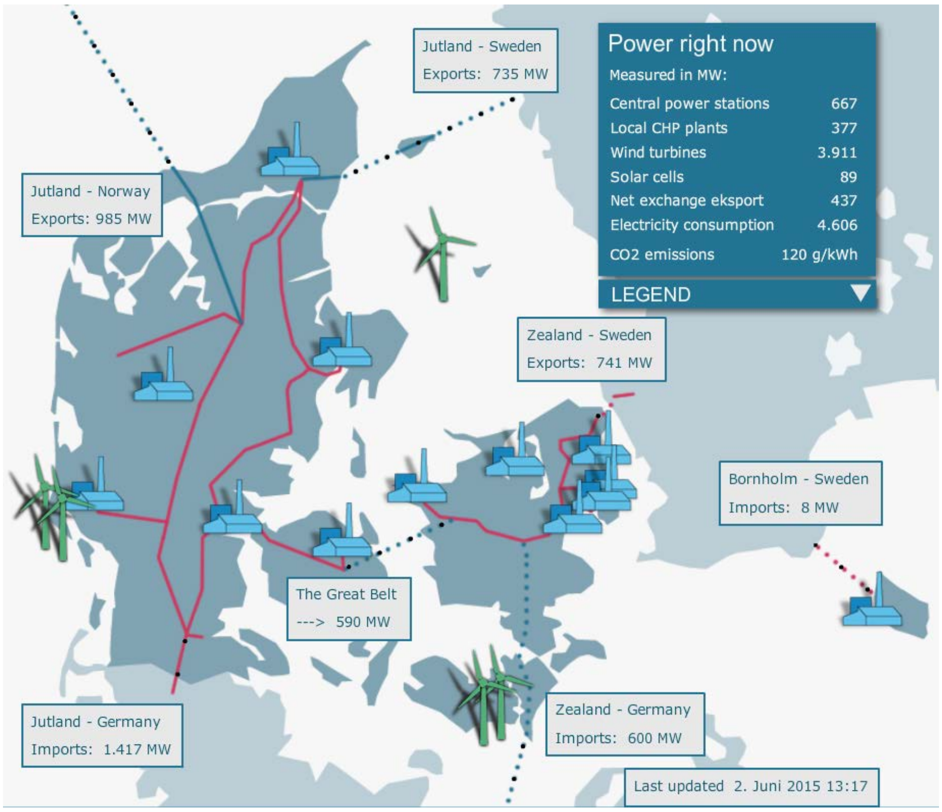


Figure 8-1: Snapshot of the Danish power system on 2 June 2015 at 13:17. The blue buildings represent central power stations, the green wind mills are offshore wind farms. Red lines indicate an AC transmission line and blue dotted lines depict a DC transmission line. Source: Energinet.dk.

Currently, the total technical export capacity to Norway and Sweden is 4,072 MW and to Germany 2,380 MW. Moreover, Eastern and Western Denmark is connected by a 600 MW DC connection.

Interconnectors are planned to the Netherlands (700 MW by 2019) and to the UK (1,000-1,400 MW by 2020). In addition, Energinet.dk and the German TSO TenneT have agreed to upgrade the interconnection between Western Denmark and Germany to 2,500 MW in both directions. Lastly, by 2022 Eastern Denmark and Germany will add 400 MW of indirect connected capacity via the Kriegers Flak project, which involves the establishment of two offshore wind parks, and an offshore grid connecting the two parks to one another and to Denmark and Germany.

8.1.1 Market coupling

With a strong physical transmission system in place, the question remains: how can the system contribute to the overall flexibility of the system? Just as generation planning is largely taken care of by the power market, transmission system utilisation is also incorporated in the power markets. As such, market coupling has been an important measure to ensure efficient utilisation of interconnectors. Market coupling is meant to ensure that power flows from parts of the system with low prices (and possibly high wind power generation) to parts of the system with higher prices. Within Nord Pool, Denmark has been coupled implicitly with Norway and Sweden since 1999/2000, whereas an explicit day-ahead auction was used for the connections to Germany until 2009. Explicit auctioning means that the transmission capacity on an interconnector is auctioned to the market separately and independently from the market places where electrical energy is auctioned. Because the two commodities – transmission capacity and electrical energy – are traded at two separate auctions, there is a risk that the flow on the interconnectors will go in the opposite direction of what the market prices would suggest. Since 2010, market coupling to Germany is implicit in the market algorithm

A comparison of the level of wind power generation in Western Denmark and the magnitude and direction of power flow on the interconnectors to Norway and Sweden reveals a clear correlation (Figure 8-2). When Danish wind power production is high, the interconnectors are predominantly used for export, and vice versa. This indicates that Norwegian and Swedish energy systems are used as a form of storage for Danish wind power.

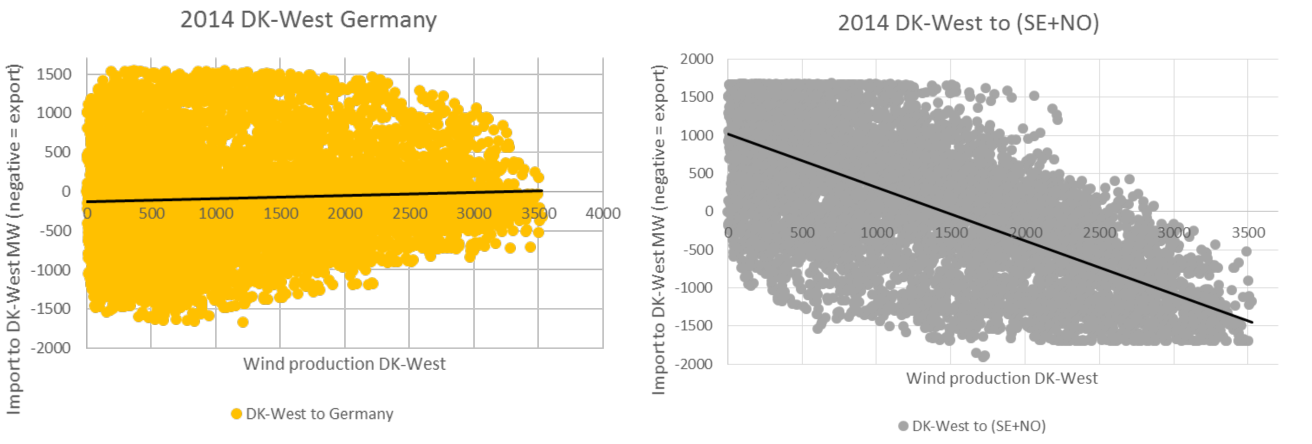


Figure 8-2: Correlation between wind power generation in Western Denmark and flows to Sweden/Norway and Germany. Source: Own elaboration, based on data from Energinet.dk.

The interconnector between Western Denmark and Germany shows no clear correlation between wind power generation and transmission. Particularly notable is the fact that as soon as Danish wind power production exceeds around 1,000 MW (less than one third of total capacity in Western Denmark) the full export capacity is currently not utilised. The reason are simultaneous high wind penetration rates in the Northern German system and congestions in the internal German transmission system. Improved flexibility in the southbound transmission system would therefore require increased capacity on the internal German grid.

8.2 Flexibility in conventional power plants

As was outlined above, the high share of wind power that has developed in Denmark over the last 25 years has provided an early incentive for increasing the flexibility of thermal power plants. From the power plants' perspective, the high fluctuation of residual load resulting from the high share of variable wind power generation leads to steep load gradients. It also requires fast start-ups at low cost, and as low minimum stable generation as possible.

Figure 8-3 illustrates the challenge for thermal power plants resulting from increased fluctuations of residual load. In the case of a renewable power shortage (load exceeds RES-E generation), there is an increasing demand for steep positive load gradients on running plants, as well as a need for fast start-ups of hot, warm or cold thermal plants. Vice versa, steep negative load gradients on running plants and as low minimum stable generation as possible are required in case of a renewable power surplus. In between these two cases, rapid fluctuations of residual load require large positive/negative load gradients.

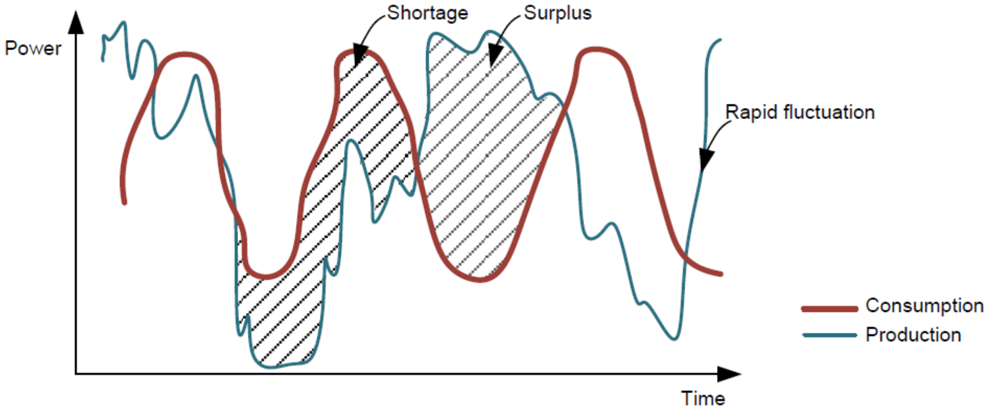


Figure 8-3: The flexibility challenge for thermal power plants as a result of fluctuating consumption and VRES-E production. (Blum & Christiansen, 2013)

As a result, Danish coal power plants that had originally been designed as base load units have been transformed into some of the most flexible power plants in Europe. Already today, load gradients of 4%PN/min for coal-fired units (9%PN/min for gas turbines) are considered the Danish standard. The minimum load could be decreased down to 10%PN and a fast start is possible within less than 1 hour.

According to involved engineers[7], the transformation process has been subject to a number of prerequisites that had to be fulfilled in order to achieve the projected flexibilisation. These include precise knowledge of the existing limits combined with the willingness to take risks during the implementation phase, adaption to local conditions, as well as full acceptance throughout the organisation.

As a result, a number of suggestions can be derived as best practice to adapt the Danish experience to other power systems. The organisational integration of the optimisation procedure is illustrated in Figure 8-4. As a first step, long-term scenario studies (10-20 years) are required in order to assess the expectable magnitude of increasing load fluctuations. Next, the economic value of all available flexibility measures have to be estimated, followed by a ranking of different options for prioritisation. The power plant portfolio can then be optimised in a top-down approach through development of adequate software. Finally, the individual optimisation of each power plant can be conducted in an iterative, step-wise approach after determining flexibilisation bottlenecks through data analyses and operator interviews and defining achievable flexibility levels. This procedure applies for improving load gradients as well as decreasing minimum load, start-up time and start-up costs.

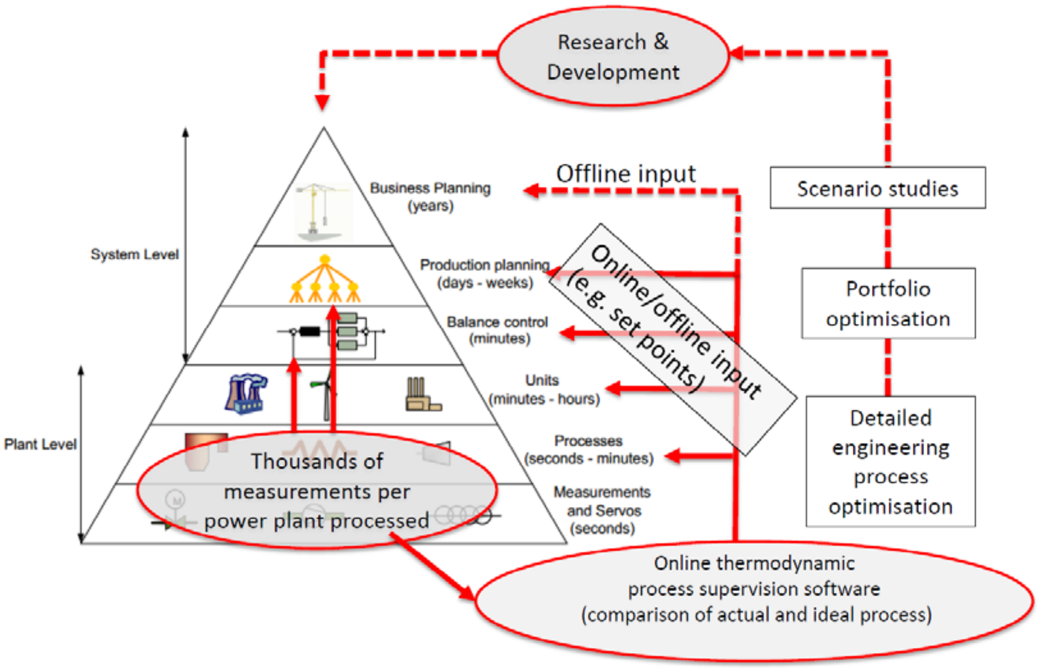


Figure 8-4: Optimisation of power plant flexibility at different organisational levels. (Blum & Christiansen, 2013)

8.2.1 Flexibility of German and Danish power plants

Denmark and Germany have a number of electricity transmission interconnectors, share a border, and have access to the same power plant technology. As such, it is interesting to compare the flexibility parameters of Danish and German power plants.

[7] The content of this section is based primarily on a presentation by Rudolph Blum, former R&D director for power plant development at ELSAM/DONG Energy and Torkild Christensen, former engineer for design, optimisation and flexibilisation of thermal power plants at ELSAM/DONG Energy

Table 8-1 displays an overview over flexibility parameters of Danish and German power plants comprised from different sources. It reflects the generally higher flexibility of gas-fired power plants as compared to coal-fired power plants. Open cycle gas turbines (OCGT) and gas-fired steam turbines (ST) are superior to combined-cycle gas turbines (CCGT) in terms of flexibility. However, the overall efficiency of CCGT power plants is higher, which is not reflected in the table. Overall, Danish power plants are more flexible than their German counterparts in all regarded categories.

Fuel and plant type	Country	Status	Positive load gradients (% P_N/min)	Min. stable generation (% P_N)
Coal ST	DK	prevailing[1]	3-4	10-20
	DE	prevailing[1]	2-3	45-55
	DE	prevailing[2]	1,5	40
	DE	state of the art[2]	4	25
	DE	optimisation[2]	6	20
Nat. gas ST	DK	prevailing[1]	8-10	<20
Nat. gas OCGT	DE	prevailing[2]	8	50
	DE	state of the art[2]	12	40
	DE	optimisation[2]	15	20*
Nat. gas CCGT	DK	prevailing[1]	3	50-52
	DE	prevailing[2]	2	50
	DE	state of the art[2]	4	40
	DE	optimisation[2]	8	30*

Table 8-1: Typical prevailing and possible flexibility parameters for thermal power plants in Denmark (DK) and Germany (DE). ST = steam turbine, OCGT = open cycle gas turbine, CCGT = combined cycle gas turbine. *The lower limit of minimum generation of gas turbines is constrained by emission threshold values for nitrous oxide and carbon monoxide. Sources: [1] (Blum & Christiansen, 2013) (values for 2011); [2] (Feldmüller, 2013)

The prevailing load gradients of existing Danish coal power plants (3-4% PN/min) already achieve what is labelled as possible state of the art of German technology. Average German coal power plants fall behind with only 1.5% PN/min. The minimum stable generation of Danish power plants at 10-20% PN is even smaller or equal than the optimisation potential stated for the German plants (20% PN). German coal power plants are still subject to minimum generation of 40% PN on average.

Danish natural gas-fired steam power plants achieve load gradients of up to 10% PN. German data on gas-fired steam power plants are not available for direct comparison, but the available data reveals that Danish gas-fired steam power plants already exceed German open cycle gas turbines, which is regarded as the most flexible power plant technology in Germany.

The load gradients of Danish CCGT power plants are slightly higher than the those of their German counterparts, while minimum generation is on the same level. For power plants based on gas turbines (OCGT as well as CCGT), the minimum generation achievable through optimisation is limited by threshold values for maximum permissible emissions of nitrous oxides and carbon monoxide. Natural gas-fired steam turbines are not subject to this limitation, because of the different combustion process.

According to Feldmüller (Feldmüller, 2013), thermal power plants in Germany are not utilising their full technical flexibility potential. As a reason for falling back behind state of the art, the source identifies lack of incentives. For example, the required load gradients for primary balancing power in Germany are at 2% PN/30sec as compared to a stricter 10% PN/10sec in the UK (status 2013). This lack of regulatory incentive is accompanied by a lack of financial incentive to invest in more flexible solutions.

8.2.2 Concrete steps

In order to address the growing challenge of fluctuating load, efforts have been undertaken over the past 15-20 years to enable increased load flexibility, reduce minimum load, and steepen ramp rates. A number of prerequisites had to be fulfilled for this purpose. In the exemplary case of DONG Energy and its predecessors, all improvements were based on own expertise, which required technical knowledge of the relevant engineering disciplines. All involved engineers were provided with access to reliable power plant process data with high resolution over many years of operation. It was ensured that control room operators underwent thorough theoretical and practical education. Thereby, control room staff could be directly involved in optimising the power plant's operation. They were instructed to continuously seek further improvements of flexibility and develop suggestions for respective modification of design and control. The implementation of optimisations was carried out in close dialog between operators and engineers.

8.2.3 Stepwise approach for optimising power plant flexibility

A stepwise approach has been applied for achieving considerable flexibility improvements in Denmark. The approach is illustrated in Figure 8-5 for the case of minimum load reduction. It is equivalently applied for increasing ramp rates and to optimise start-up.

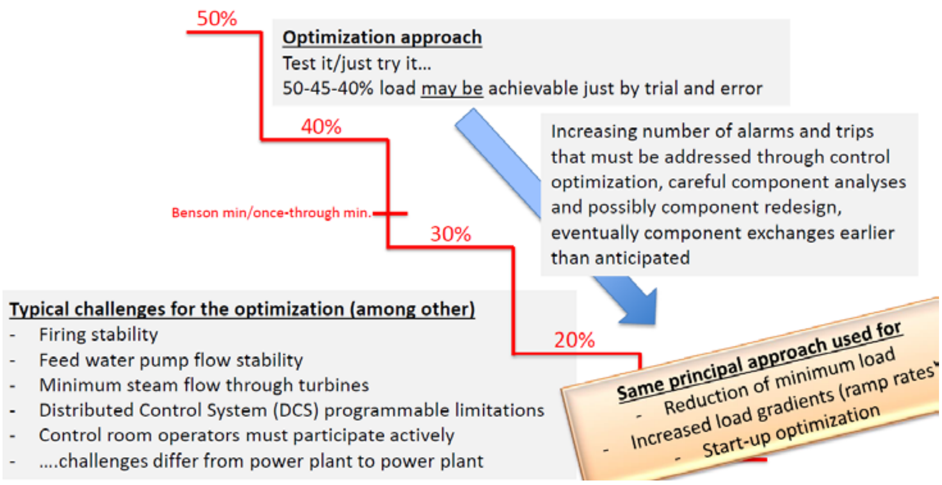


Figure 8-5: Stepwise approach for increasing power plant flexibility. (Blum & Christiansen, 2013)

Firstly, load is carefully reduced until the first bottle-neck appears. Subsequently, the observed problem is analysed with the goal to find an adequate solution. Finally, the load can be further reduced until a new limitation appears. With an increasing amount of iterations, the amount of failures and alarms increases. Therefore, it is essential that the unit is thoroughly protected by alarms and warnings and all required measurements must be continuously calibrated and maintained.

The typical solutions to flexibility problems are often achieved by control optimisation and possibly component redesign based on careful component analyses. In some cases, the new process parameters will exceed design limitations, which require an exchange of components earlier than originally anticipated. The optimal trade-off can be determined by means of respective cost-benefit analyses. The optimisation challenges vary from plant to plant. Based on the Danish experience they typically comprise firing stability, feed water pump flow stability, minimum steam flow through turbines and program limitations of the Distributed Control System (DCS).

8.2.4 Examples for flexibilisation of Danish plants

Two examples shall illustrate the Danish approach and achievements of power plant flexibilisation. Firstly, an exemplary optimisation routine shows how start-up time can be reduced. Secondly, the daily cyclic operation of a Danish power plant demonstrates the realisation of low minimum load and steep ramp rates.

The optimisation of a coal power plant commissioned in 1998 shall serve as an example for the reduction of start-up time. The suggested measures are expected to yield a reduction by 28%, from 131 to 94 minutes. The procedure of the power plant start-up with and without optimisation is shown in Figure 8-6. The most relevant improvements are to be achieved within the early phase of the start-up by keeping vital components at a higher temperature. This decreases the time required for providing superheated steam to the turbines. As a result, grid synchronisation is possible within 60 instead of 90 minutes.

In the next optimisation step, the ramp up time from the point of grid synchronisation to full generation capacity is reduced by 7 minutes. This is achieved by replacing the old rigid, non-reprogrammable control software with a new one that allows for flexible adaption of start-up criteria.

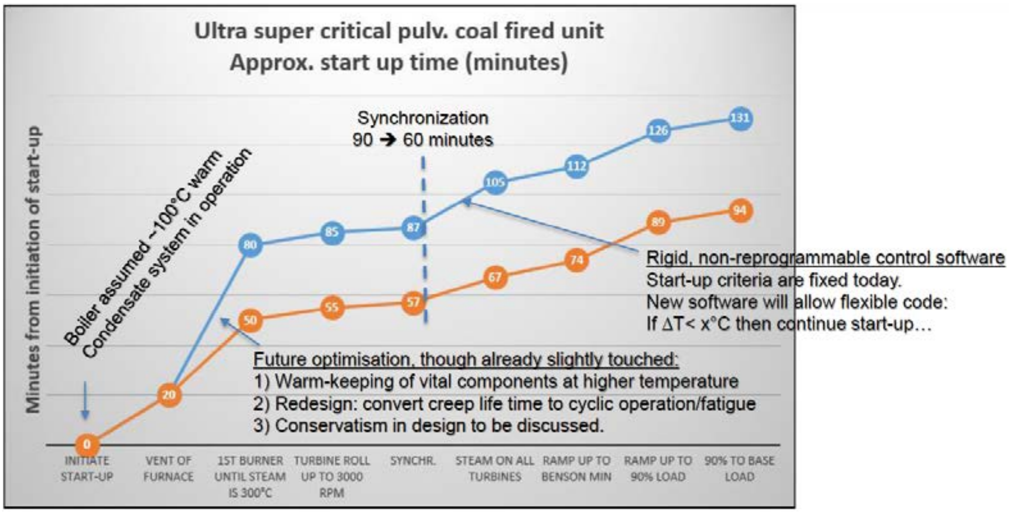


Figure 8-6: Start-up optimisation of a coal power plant. (Blum & Christiansen, 2013)

Figure 8-7 displays the daily cyclic operation of a Danish natural gas-fired steam power plant for a selected day. It provides an example for low minimum load and steep ramp rates. During the night, the power plant operates below the so-called Benson minimum. The Benson minimum represents the boiler load above which the evaporator feedwater can circulate autonomously. Below this limit, forced circulation is required to maintain sufficient flow rates. The graph indicates that the Benson limit is passed several times per day, which deviates from original design criteria. This leads to increased stress on the components, which can cause early fatigue. Therefore, a component redesign may be required. Alternatively, the replacement intervals can be shortened for affected components. In the regarded case, assessments concluded that the components would endure the more flexible mode of operation without compromising their lifetime.

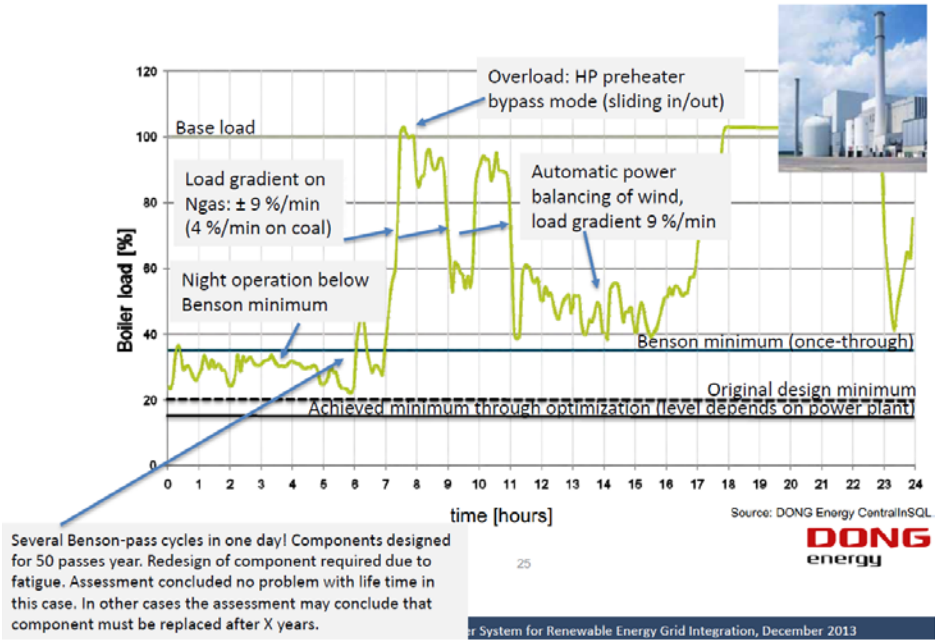


Figure 8-7: Daily cyclic operation of a gas fired Ultra Super Critical steam power plant. Source: Blum and Christensen 2013

The figure also illustrates steep ramp rates, which correspond to a maximum of 9%PN/min for the example gas-fired steam power plant. For Danish coal power plants, 4% PN /min are standard. The achievable ramp rates help the power plant to adapt to steep load gradients and enable automatic balancing at a high variability of load.

Lastly, the figure shows that the rated capacity can be exceeded at times of high load. This overloading is achieved by bypassing the high pressure preheater in the steam cycle.

8.3 Power to heat

A very large portion of Danish electricity production is connected to the district heating system. With the exception of a few plants, all power plants in Denmark have the possibility of co-generating electricity and district heat. This results in restrictions with respect to the ability to integrate wind, as options for electricity production are to some extent limited by the requirement to supply the heat demand. However, integration of the power and district heating sector also provides opportunities for enhanced integration of variable renewable energy. Indonesia does not have a district heating system. However, the concepts of combined heat and power as well as the options to integrate the heat and power sector also apply for industrial process heat usage, which could prove to have some relevance for Indonesia.

The production of cogenerated heat is environmentally and economically sensible as long as the alternative is letting the heat produced go to waste. However, in order to fully utilise the electricity produced by wind, it will become increasingly environmentally and socioeconomically attractive to decouple this link between heat and electricity production and in some situations, it can be necessary to stop cogeneration of electricity and heat all together.

Most central plants are CHP plants, which can switch between producing only electricity (referred to as condensation mode), and producing both district heat and electricity. In combined heat and power mode, the low-pressure turbine can be bypassed, ensuring heat production at sufficient temperature. When extra power production is needed, the low pressure turbine will be used fully, and district heat generation will be omitted (see Figure 8-8). This flexibility offers the opportunity to increase power generation within a very short time horizon, e.g. for balancing fluctuations in the power system. Today, this ability is used by Danish power plants to optimise operation according to the power prices (day-ahead or intra-day) and to provide ancillary services.

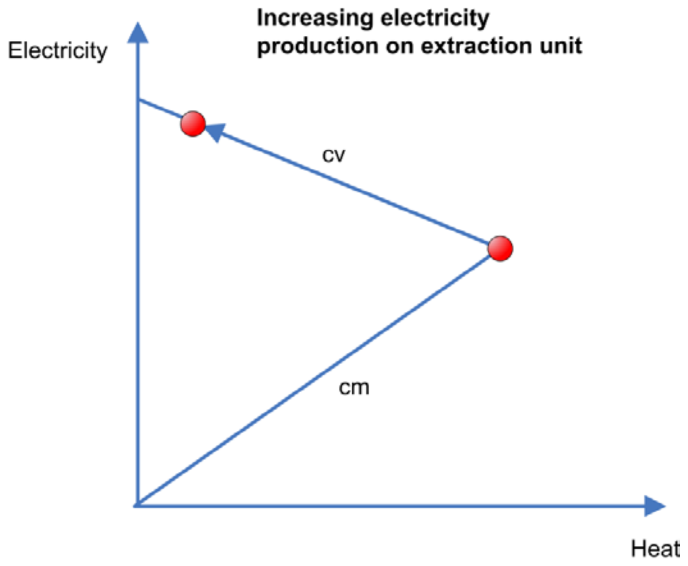


Figure 8-8: Illustration of operation points with different electricity to heat ratios for a combined heat and power extraction plant.

Smaller decentralised power plants are mainly so-called 'backpressure steam plants', which produce electricity and heat at a particular ratio. They can normally only produce electricity when they also have the possibility of supplying heat to the district heating system. However, it is possible to retrofit these back-pressure power plants with cooling options. For smaller decentralised plants this would be air cooled condensers. In Denmark today, this option is mainly used at biogas-fired CHP-plants, which want to use the available biogas production during summer time, when district heat demand is low.

Some larger power plants have the option to let the steam bypass the turbines and use it directly to produce heat if they have installed a 'steam bypass' system.[8] As such, when CHPs use steam bypass they effectively function like a boiler. This enables power plants to avoid electricity generation at times with low electricity prices (e.g. due to high wind penetration), while avoiding a complete shutdown of the plant and continuing heat generation.

[8] Steam bypass is most relevant for steam turbine cogeneration plants (there is a total of 5 GW steam turbine cogeneration plant capacity in Denmark).

Heat storages have been established in conjunction with the majority of the Danish CHP plants. Heat storages increase the flexibility of the electricity system as the CHPs can reduce or stop production of heat and electricity during windy periods, and instead supply their heating customers with heat from the heat accumulators. Likewise, CHPs can supply electricity during times with low wind generation and store the heat production. Larger heat storages are one option for improving the flexibility of a system characterised by both a large share of wind power, and a large share of cogenerated heat and power.

A way to ensure the value of variable electricity generation is to introduce new electricity consumption at times with high electricity generation. One option is to use electricity to produce heat, for example through the use of centralised electric boilers or high efficiency heat pumps connected to the district heating system. In terms of energy input/output, heat pump systems can supply up to 4 times as much heat compared to the electricity they use, and can thereby contribute to a highly efficient overall energy usage. On the other hand, heat pump systems involve significant investments. An alternative to heat pumps with a substantially lower investment cost is electric boilers. However, they are also much less efficient, as one unit of electricity is converted to one unit of heat. Heat pumps are therefore well suited for applications with many operating hours, whereas electric boilers are more cost-effective for applications involving fewer operating hours.

The optimal operation of the integrated power and district heating system depends on the power price. Low power prices will often indicate high generation from variable renewable energy, while high prices indicate a need for additional power generation. Figure 8-9 displays a comparison of the heat production price from different units, depending on the electricity price.

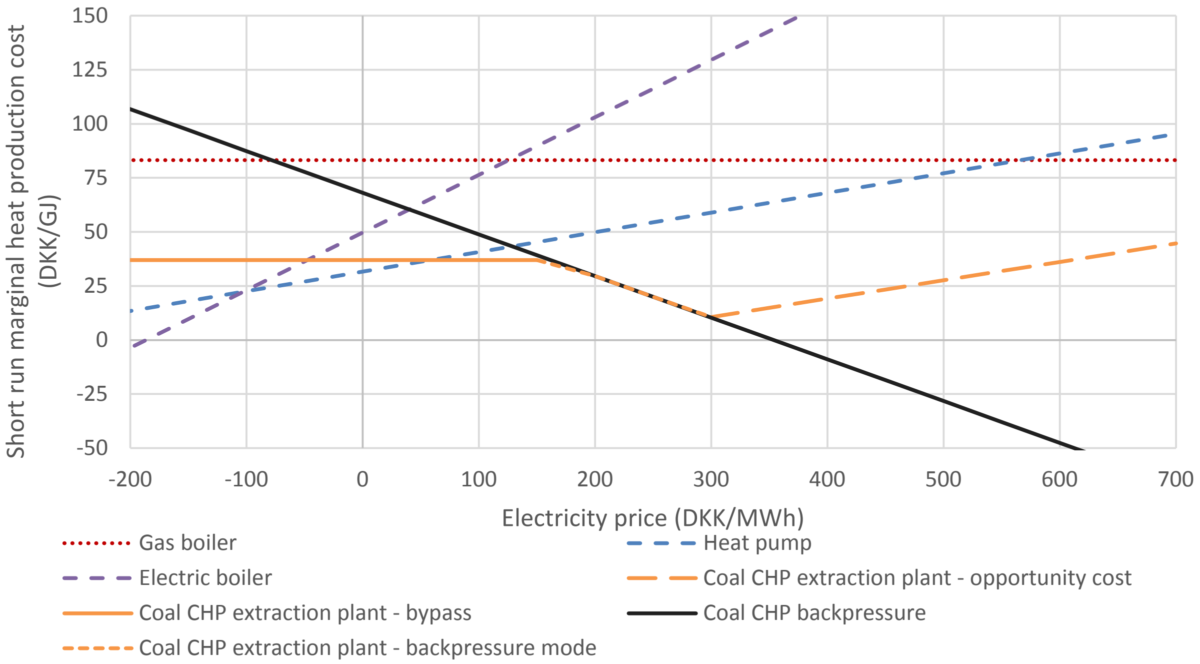


Figure 8-9: Short run marginal heat production price for different units depending on the electricity price. Illustrative example. Actual prices will depend on fuel prices, emission prices and taxes and subsidies.

At very low (negative) electricity prices, electric boilers offer the cheapest price, since the boiler can earn money by consuming electricity. As electricity prices rise, it can be cheaper to use first the more efficient heat pump, and then the turbine bypass on the CHP-plant. At higher electricity prices, it is economically sound to run the CHP plant in backpressure mode. If the CHP-plant is an extraction unit, with very high electricity prices, opportunity costs will occur, since the plant could choose to produce more electricity when omitting heat production thereby increasing income. As a result, at very high electricity prices, the gas boiler will therefor provide the cheapest option.

8.4 Demand response

Aside from the installation of interconnectors and other measures implemented on the supply side, the introduction of flexible demand constitutes an important option for enhancing the dynamic capabilities of the power system. To date, demand response has not been important to the integration of wind power in Denmark, but there are expectations – and hopes – that this will change. However, demand response is especially relevant for power systems with very high shares of variable renewable energy, and does not need to be among the first measures to be used when wind power is introduced into a system.

There are different ways of increasing demand flexibility (Ea Energy Analyses, 2011a):

- Load shifting: This refers to the shifting of demand by household consumers (e.g. for cooling) and industrial customers from a period with high electricity prices to a period with low electricity wholesale prices.
- Peak shaving: Refers to a reduction in peak demand during times of high prices. This may comprise consumption that is simply reduced, but not shifted to another period (e.g. lighting in shop windows when the shops are closed).
- Fuel shift in industries: Substitution of currently utilised fuel (oil or gas) to electricity based process heat when electricity prices are low.
- Indirect usage of electricity by means of hydrogen: electricity used for local or central production of hydrogen in order to replace natural gas. This solution is not likely to play a role in the short to medium terms as it requires reductions in investment costs for electrolysers as well as many hours with low wholesale electricity prices.

8.4.1 Demand response in the electricity market

For customers in, e.g. Denmark, with a large electricity demand, it is easy to be active with demand-side flexibility. The electricity used by the company is accounted for based on hourly consumption, and the company may choose to buy electricity at the spot price with free volume. The term “free volume” means that the company does not have to report the amount of electricity it will use the next day. The retailer will predict the demand for all its customers, based on historic demand. With many customers, demand is relatively easy to predict (based on information about the type of day and outdoor temperature).

The company receives the next day’s prices around 1 p.m. the day before. If the company has processes that can be performed at alternate times, then this can be done to minimise demand during expensive hours, and maximise demand during the cheapest hours. The company can develop its own strategy (e.g. if it will react to price data every day, or only when the price difference is high).

With this set-up, demand-side flexibility is straightforward for the end-user, and the flexibility will enter the market as price-dependent bids, thus influencing price formation.

Currently, other end users (<100,000 kWh/year) cannot receive economic benefit from demand-side flexibility as the profiling system[9] does not allow for this. For ancillary services, demand-side flexibility is not practical, as the procedures and rules in place were designed for generators. Both areas (the profiling system and procedures for ancillary services) are under development. According to Energinet.dk, a new hourly settling system should be ready by July 2016 (Energinet.dk, 2015e).

8.4.2 Fuel shift in industries

Even though the manufacturing sector in Denmark is relatively small there is a significant potential for flexible electricity consumption in the industry sector. This particularly involves a “fuel shift”, i.e. substituting the fossil fuels that are currently used with electricity based process heat, either from electric boilers or potentially high temperature heat pumps, when electricity prices are low. Since the industry sector utilises much shorter payback periods than those used, for example, in the district heating sector, this can however pose a significant barrier for exploiting fuel-shift opportunities.

8.4.3 Storing electricity

A number of technologies have been discussed with a view to storing electricity locally in Denmark, including compressed air storage, batteries, flywheels, hydro reservoirs, and hydrogen production in combination with fuel cells. All of these technologies are technologically possible, but they require large investments. Also, the majority of these technologies are associated with significant energy losses.

In 2014, the Danish Energy Agency published four different scenarios showing how Denmark could meet the vision of a fossil fuel independent energy system by 2050 (Danish Energy Agency, 2014b). Direct electricity storage in Denmark is not included in any of the scenarios. The preliminary assessment from the Danish Energy Agency is that use especially hydropower storage facilities abroad and flexible electricity consumption are cheaper solutions.

However, two of the scenarios – including the so-called wind scenario, which was the favoured scenario by the former minister of climate and energy – foresee large-scale hydrogen production. The hydrogen is used to replace biomass and biogas to make it last longer, as biomass may become a scarce resource in the future. At the same time, the electrolyser factories provide a source of relatively flexible electricity demand, improving the integration of wind power.

8.4.4 Smart grid strategy

In 2013, the Danish government set forth a “Smart Grid Strategy” for the future development of the power grid (KEBMIN, 2013). The strategy was developed in cooperation with relevant Danish stakeholders, including Energinet.dk and the Danish Energy Association. It details a broad range of initiatives to be implemented by the government and power sector (see text box).

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[9] The profiling system helps convert long-term meter readings (i.e. over one year) into hourly values. In this way, demand from users without smart meters can be part of the planning and settlement of the market. In the Danish profiling system, the profile is computed based on the residual demand in each grid company. That is the total electricity delivered to the grid area minus the demand from users with hourly settlement and minus grid losses. Therefore, all small end users in a specific grid area have the same profile. In other countries, like Finland and the Netherlands, the profile is defined for different types of consumers.

According to the strategy, two important preconditions need to be met in order to develop the potential for demand response:

- Consumers should have hourly meters installed that can be accessed remotely, and
- The electricity market should allow consumers to be settled on an hourly basis instead of the fixed-price settlement (known as template settlement) used today.

The "Smart Grid Strategy" sets forth a broad range of initiatives to be implemented by the government and energy sector, including:

- Changes to the economic regulation of grid companies to promote investment in smart grid technologies
- Improving access for small consumers to the market for ancillary serves
- Changes to the electricity tariff system to reflect the benefits of flexible load
- Changes to building regulations to promote flexible heat pumps in new buildings
- The promotion of "smart" appliances through EU regulation (Eco design directive)
- Funds for showcase activities
- Analysis of the interplay between electricity, heating and gas sectors

The government's "Smart Grid Strategy - The intelligent energy system of the future" from 2013 (KEBMIN, 2013) describes a scenario for development in the theoretical potential for flexible electricity consumption for a number of technologies up to 2035 (see Figure 8-10). The potential identified for 2035 is just above 8 TWh.

Until now, however, it has proven difficult to realise the potential for demand response.

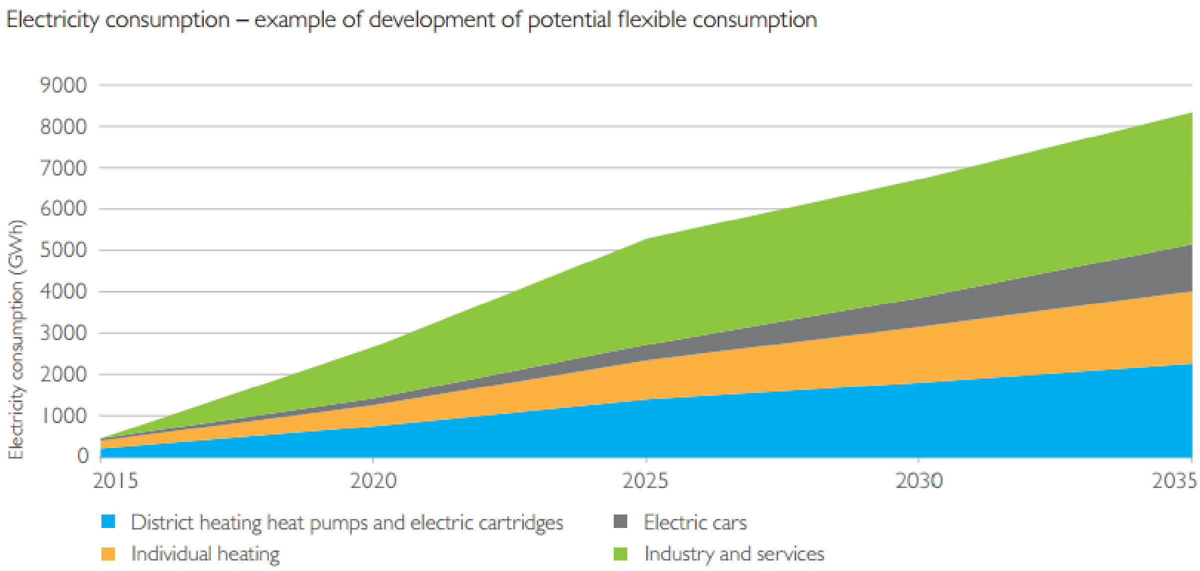

Figure 8-10: Electricity consumption – example of development of flexible consumption. Source: Danish Ministry of Climate, Energy and Building, Smart Grid Strategy The intelligent energy system of the future (KEBMIN, 2013), p. 11.

8.5 Ancillary services

Traditionally, most ancillary services such as reserve capacity, inertia, frequency control and voltage control were provided by large thermal power plants. Central power stations used to produce a significant amount of power during hours with low electricity prices. This was partly due to technical restrictions on the plants themselves, and partly due to power system requirements.

Energinet.dk's strategy is to build the system stability components into the grid when this is economically advisable. This includes Static Var Compensators (SVC), static synchronous compensator (STATCOM) equipment and synchronous condensers. The benefit of these components is that they can provide the services required alone without co-generation of electricity (Energinet, 2011). This means that required ancillary services to support system reliability such as continuous voltage support or voltage support during fault can be delivered by these components. In turn, this may contribute to the reduction of must-run capacity in power generation. Apart from the dedicated devices mentioned in this section, grid codes are used to ensure certain technological capabilities by generators and subsequently reduce the requirements for dedicated devices (see section 9.2).

Table 8-2 provides a summary of the various technologies' ability to provide the properties required.

	Power station >100 kV	Power station <100 kV	Wind turbine >100 kV	Wind turbine <100 kV	Classic HVDC	New HVDC	SVC/STATCOM	Synch. cond.
Inertia	++	+	(+)	-	(+)	(+)	-	++
Short-circuit power	++	+	(+)	-	-	(+)	-	++
Black start	(++)	(+)	-	-	-	(++)	-/+	-
Continuous voltage control	++	(+)	(+)	-	-	++	++	++
Voltage support during fault	++	-	++	-	-	++	++	++
Power system stabilisation (PSS)	+	-	(+)	-	(++)	(++)	(+)	-

Table 8-2: Assessment of the properties required to maintain power system stability (provided by different sources). ++ "Large contribution", + "Some contribution", (+) "Conversion possible", ÷ "Unsuitable". Source: Energinet 2011: Energinet.dk's ancillary services strategy.

The Voltage Source Converter (VSC) technology, which is used on new HVDC connections, is capable of providing most of the properties required, except inertia. However, "Energinet.dk does not consider inertia a critical factor for safe operation of the Danish power system. This is due to the fact that Eastern and Western Denmark are connected to the large interconnected synchronous areas in Scandinavia and Continental Europe, respectively. [...] Therefore, Energinet.dk does not in the short, medium or long term see a need for forced operation of power stations for the sake of procurement of sufficient inertia" (Energinet.dk, 2013: Amendment to Energinet.dk's ancillary services strategy, p. 7f.).

Energinet.dk has held a number of tenders for the provision of system services. Among other things, the tenders have requested the delivery of a synchronous compensator or the equivalent performance of a converted power station. In all cases, the establishment of a new synchronous compensator has been the economically cheapest alternative.

In light of the above, the need for must-run capacity has been reduced from 3 large units to 0-1 units in Western Denmark. In Eastern Denmark the requirement has been reduced from 2-3 to 1-2 units. Towards 2018, a number of projects to strengthen the grid and expand international connections are expected to further reduce the need for must-run capacity (Energinet.dk, 2013: Amendment to Energinet.dk's ancillary services strategy).

8.6 Discussion – discussion on possible measures that could be taken to increase the flexibility in the Indonesian power system

In the Danish and North European context the predominant means for efficient integration of variable renewable energy are

- Strong transmission grids and interconnectors
- International electricity markets
- Flexible generations systems
- Specialized forecasting and operational planning tools (see chapter 7)

In an Indonesian context some of these are more relevant than others.

Denmark is an integrated part of the North European electricity market and is heavily interconnected with a strong transmission grid. Denmark is a small country and the domestic electricity generation capacity is dominated by wind power and thermal plants fired by coal, gas and biomass.

The strong transmission grid and interconnectors enable Denmark to balance the variable wind power in a larger and more diversified electricity system in the Northern European region. The coupled electricity markets ensure optimal utilisation of the available transmission capacity to supply demand with the cheapest possible generation capacity in the region. At the same time, the transmission system ensures crucial access to storage capacity in the hydro based electricity system in Norway.

For Indonesia, the international dimension on both transmission grids and electricity markets are very limited, and focus will have to be on domestic solutions. However, the domestic system is considerably larger than the Danish, and options for integration of variable generation can therefore still be obtained within the system.

The strong transmissions grids are still relevant with a larger share of variable renewable energy, which inevitably will create larger and more fluctuating flows on the transmission and distribution grids. Wind power will often be located far away from demand centres and substantial grid investments required to avoid curtailment.

For Indonesia, the flexibility of the thermal generation system is very important for the optimal utilisation of the wind power generation. The flexibility of the Danish thermal plants have increased substantially along with the massive integration of wind power, and sharing of Danish experiences on this process could be of great value for the Indonesian electricity utilities.

Indonesia's smaller island power systems might need focus on different and to some extent more advanced measures for integration, compared to larger power systems, as the European of which the Danish system is a part. For a case study on a smaller Island system, see chapter 10.3.1. As an example, batteries can be relevant for smaller isolated systems, while they are still too expensive compared to other options in large power systems. In smaller systems alternative generation can be costlier, which increases the value of batteries.

Other topics for ensuring sufficient power system flexibility include:

- Small systems can require other technologies as e.g. batteries for integration of variable generation as opposed to the larger interconnected system.
- Power to heat – Industrial demand for process heat could provide demand flexibility if options for fuel shift are implemented (electric boilers as backup for alternative fuel based heat generation)
- Demand response, especially from larger customers
- Alternative providers of ancillary services

8.6.1 References

1. Ea (2015): The Danish Experience with Integrating Variable Renewable Energy. Study on behalf of Agora Energiewende
2. Danish Energy Agency (2015): Flexibility in the Power System – Danish and European Experiences

9 Grid connection of wind power plants in Denmark

This chapter will present the approval process for new onshore and offshore wind farms in Denmark. It likewise presents the grid codes for wind power plants and discusses how grid connection is handled in Denmark, and which technical studies are to be conducted before granting grid connection. At the end of the chapter a discussion is made regarding possibilities of requirement and technical studies that can be assessed as part of the approval process for grid connection of wind turbines into the Indonesian grid.

9.1 Approval process of wind power plants in DK

The process of granting a grid connection takes its point of departure in the type certification of a wind turbine, the electrical characteristics, the control and monitoring capabilities, the environmental assessment and approval of the site for the wind power plant. This chapter will address the electrical characteristics and the control and monitoring capabilities of the wind power plant facility.

The fundamental document for granting a grid connection in Denmark is the type certificate for the wind turbines applied in the facility, and the Danish registration in the DEA register of wind turbines allowed to be erected in Denmark. The rules and procedures are described the Danish Energy Agency's Executive Order on The Technical Certification Scheme for wind turbines no. 73 of January 25th 2013 and the appurtenant guideline. Wind turbines, including foundations, to be installed, maintained and serviced in Denmark must be certified according to the requirements in the Danish Certification Scheme. Based on the certificated wind turbines a wind power plant can be designed and approved by the relevant authorities.

Based on the executive order from the Danish government, the TSO (Energinet.dk) and DSO's is obligated to bring the grid connection point in the proximity of the wind power plant site. This includes also offshore wind power plant sites. The only difference between granting a grid connection to an offshore wind power plant compared to an onshore wind power plant site is that the collection of endorsements involves a specific authorisation for operating offshore as the offshore territory is owned by the Danish state.

When applying for a grid connection, the facility owner follows the process depicted in figure 9-1. The procedure to follow is the same or granting the grid connection in the transmission or distribution system. The electricity undertaker (TSO/DSO) is the one to decide where the point of connection shall be allocated.

Based on a compliance test document approved by the grid operator a final operational notification can be issued and the facility owner is allowed to operate the facility.

Each third year a regular review / inspection of the actual compliance status is performed. Such an inspection could result in an interim operational notification and a new compliance test shall be performed after a maintenance or repair.

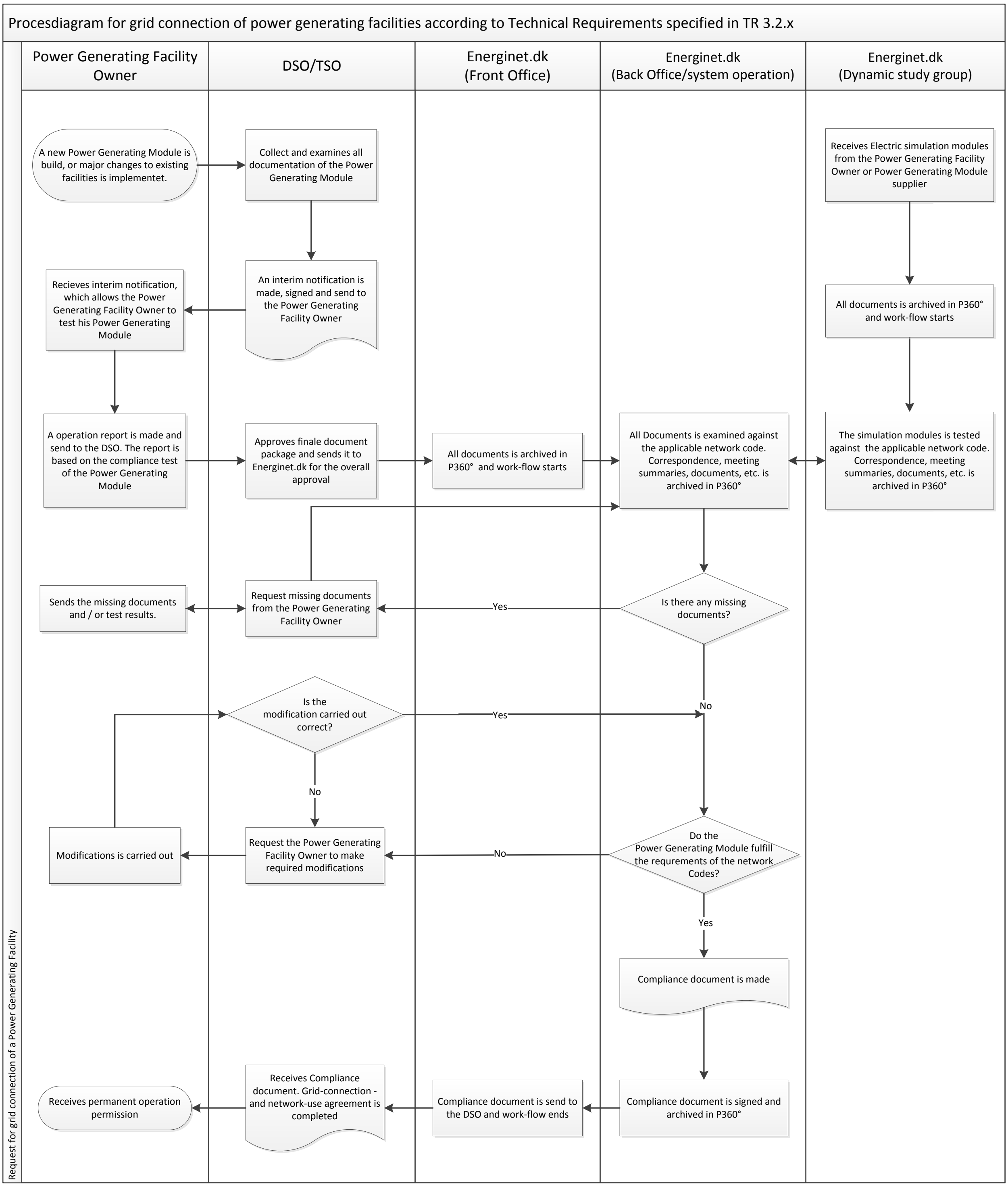

Figure 9-1: Grid connection granting procedure applied in Denmark.

9.2 Technical requirements in a grid connection code for wind power plants

The relation between the various network codes are depicted in the figure below as are the actual European network codes. The connection codes specify the minimum requirements for functionality and attributes of the generating (RfG), as well as the demand facilities (DCC). In addition, a connection code for HVDC systems is also created. Based on the available functionality and attributes the facility can be operated.

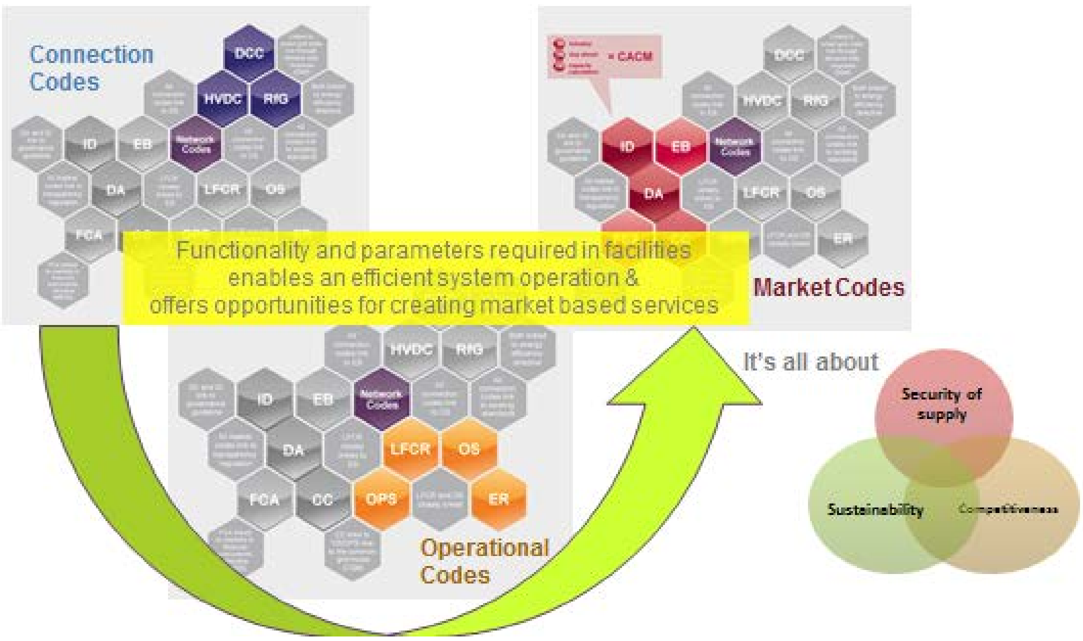

Figure 9-2: Relation between the various European network codes

The operational codes include the requirements for the Operational Security (OS) aspects, Operational Planning and Scheduling (OPS) as well as Load Frequency Control and Reserves LFCR). All facilities shall be operated within their available functionality and attributes as well as the characteristics of the fuel applied (wind, solar, biomass etc.).

The general grid connection codes structure includes requirements to be fulfilled for the following technical areas:

a) Stability impact and requirements related to facility size
b) Requirements on facility robustness
c) Requirements on power quality
d) Requirements on controllability
e) Requirements on information exchange & security
f) Requirements on documentation & verification

The following subsection describes overall structure and a general list of content for a set of grid connection requirements. The specific connection codes might be more or less specific depending on the grid topology and/or technical constraints in the grid implemented.

A. Stability impact and requirements related to facility size:
Categorisation of generation/demand facilities can be applied to assign requirements

- Impact on grid stability is related to the aggregated **size** of the generation/demand facility
- E.g. requirements for generation/demand facilities could be sorted in five categories:
    - A: generation/demand facilities from 1 kW to 50 kW
    - B: generation/demand facilities from 50 kW to 1 MW
    - C: generation/demand facilities from 1 MW to 10 MW
    - D: generation/demand facilities from 10 MW to 50 MW
    - E: generation/demand facilities above 50 MW
- All requirements shall be specified as minimum requirements

B. Requirements on facility robustness:
- Robustness against supply voltage variations
    - e.g. all facilities shall stay connected for supply voltage variations of ± 10%
- Robustness against frequency variations
    - e.g. all facilities shall stay connected for frequency variations of ± 6%
    - Robustness against voltage dips and swells
    - e.g. all facilities shall stay connected during voltage dips down to 10% of the nominal supply voltage level for up to 250 msec
    - e.g. all facilities shall stay connected during voltage swells of up to 30% of the nominal supply voltage level for up to 150 msec

C. Requirements on power quality:
- Immunity / tolerance against:
    - DC unbalance
    - Rapid voltage fluctuations
    - Harmonics
    - Inter-harmonics
    - Electromagnetic disturbance above 2 kHz
- Emission of:
    - Rapid voltage fluctuations
    - Harmonics
    - Inter-harmonics
    - Electromagnetic disturbance above 2 kHz

D. Requirements on controllability
- Controllability of active power

  Frequency related control aspects – keep nominal frequency
    - Automatic generation control
    - Automatic reserve activation
    - Ramping limitations
    - Frequency quality limits
- Controllability of reactive power

  Minimize reactive power flow control – reduction of grid losses by
    - Q- control
    - Voltage control
    - Power factor control
    - Automatic power factor control

E. Requirements on information exchange & security

- Specify a minimum set of information to be exchanged for monitoring and control and forecasting purpose
    - e.g. wind speed, wind direction, ambient temperature, air density, rain, dew point, cloud height, visibility, solar radiation
- Deploy information exchange based on international standards
    - e.g. IEC 61850(substations), IEC 61400-25(Wind Power), IEC 61970 (CIM), IEC 62325 (CIM for market)
- Deploy information security strategy based on international standards
    - e.g. IEC 62351, ISO 27000

F. Requirements on documentation & verification
- Requirements on documentation for the categories defined could be as follows:
    - Information on owner ship and location
    - Information on applied technology
    - Type certificates
    - Electrical schematics
    - Protection settings
    - Verification test reports with compliance test results
    - Final set of facility configuration parameters
    - Electrical simulation models for grid simulations integration
- Requirements on regular compliance monitoring – e.g. each three years

9.3 Grid connection of wind power plants and technical assessments

The process of selecting where in the grid a connection point shall be allocated involves a delicate study or technical assessment of the grid opportunities and constraints. Several technical aspects are taken into consideration during the study, e.g. facility size, existing generation and demand facilities and their attributes, whether the grid is cables or overhead lines, the proximity to interconnectors such as HVDC systems, prognosis on upcoming distributed generation and or demand / flexible demand.

All the technical aspects are conveyed into the national grid simulation model, and dynamic as well as steady state stability studies are carried out for the various grid scenarios foreseen. The electrical simulation models required to be provided with generation and demand facilities are integrated into the national grid simulation model and adds to the grid supporting functionality and attributes required in the facilities. Selection of appropriate operational parameters within the limits of the facilities addressed can be essential for maintaining the grid stability in various problematic scenarios.

During operation of the evolving generation and demand portfolio, parameters of the facilities can be vital to change by communication means or reconfiguration request, in order to maintain a stable grid and thereby security of supply.

9.4 Discussion

Relevant takeaways from the Danish experiences with grid connection of wind power relate to both the process and requirements for wind turbines.

The process for approval of the connection of wind turbines ensures a transparent procedure, while giving the grid operators the option to evaluate and plan for secure operation of the power system.

As the share of wind power in Denmark has risen over the past decades, technical requirements for wind turbines have been strengthened. Thereby, safe operation of the system could be ensured. Technical improvements of the wind turbines in response to strengthened grid code requirements include fault ride through capabilities and requirements for reactive power, where the most advanced wind farms are able to actively take part in voltage control instead of imposing challenges on the system as the earliest wind turbines did.

Points for further discussion include:

- How to evaluate incoming wind power projects in Indonesia?
- Possible requirements and technical studies that can be assessed as part of the approval process for grid connection of wind turbines into the Indonesian grid.
- Proposal for elements to be included in a procedure from evaluating incoming wind plant projects to commissioning:
    - Establishment of grid codes: Requirements for Generators (RfG) in place. European ENTSO-E template could serve as inspiration. Concrete values need to be calculated according to local circumstances (has to be done by Indonesian experts, but could be supported by Danish experts).
    - Studies and technical approval process regarding RfG.

9.4.1 References

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2. ENTSO-e (2016): Overview on network code development https://www.entsoe.eu/major-projects/network-code-development/Pages/default.aspx
3. ENTSO-e (2016a): Network Code for Requirements for Grid Connection Applicable to all Generators https://www.entsoe.eu/fileadmin/user_upload/_library/resources/RfG/130308_Final_Version_NC_RfG.pdf
4. ENTSO-e (2016b) IMPLEMENTATION GUIDELINE FOR NETWORK CODE "Requirements for Grid Connection Applicable to all Generators" https://www.entsoe.eu/fileadmin/user_upload/_library/resources/RfG/131016_-_NC_RfG_implementation_guideline.pdf
5. European commission (2016): COMMISSION REGULATION (EU) 2016/631 of 14 April 2016 establishing a network code on requirements for grid connection of generators http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016R0631&from=EN

10 Integration of photovoltaics

The integration of photovoltaics involves some of the same challenges as wind power, especially on an overall system level (see chapter 4). Solar power as well as wind power has a variable nature and is produced according to the availability of the resource. Accordingly, some of the same measures for integration of wind power apply to solar power:

- The importance of incentives for generators to adapt generation patterns according to system needs (chapter 6)
- The importance of operational procedures and forecast systems (chapter 7)
- The importance a flexible power system in terms of generation, transmission and demand (chapter 8)
- The importance of connection codes to ensure technical suitability and ultimately safe operation of the system (chapter 9)

However, integration of solar power also involves some differences relative to integration of wind power with respect to the characteristics of the generation patterns, integration into distribution grids, distribution of generators and forecast challenges.

10.1 Characteristic of solar power

In Northern Europe, solar resources are limited compared to wind power, and therefore solar power generation has a lower amount of full load hours per year, compared to wind power. For Denmark, the rough numbers would be around 1,000 full load hours for solar power, while new onshore wind turbines can achieve at least 3,000 full load hours depending on the technology and location. If the same share of annual generation was to be achieved in the Nordic countries by either wind or solar power, solar power would show larger integration challenges, since the generation is distributed on fewer hours, increasing balancing and storage challenges.

The daily variation profile of solar power generation correlates well with the load patterns, with higher loads during daytime. However, when the share of solar power increases, net peak demand is moved early mornings and afternoons, and the suitable correlation diminishes for further generation from solar power.

The seasonal variation patterns are less favourable in the Nordic countries, as generation is highest during summer, while demand is highest during winter due to the demand for electric heating, especially in Norway and Sweden.

10.2 Integration of solar power

The contribution of solar photovoltaic to Danish power generation has been limited to date. At the end of 2015, around 780 MW of solar capacity was installed in the Danish power system contributing less than 2% of the gross electricity demand. However, as a consequence of price reductions, solar shares in the Danish power system are expected to increase in the future. On the other hand, solar power has a more prominent role in the German power system with almost 40 GW of installed capacity and a share of approximately 7% of gross electricity demand.

10.2.1 Reverse power flows and power quality

In Germany, a large share of the solar power generation capacity is installed in the low voltage grid (both 0.4 and 10 kV), and distributed across many relatively small units. The low voltage grids, and especially the 0.4 kV grids, were not designed for generation, but the local generation can now at times exceed consumption requiring reverse flows in the power system. The reverse power flows can cause voltage problems in the low voltage grids and might call for changes in the existing transformers, protection settings and protection devices.

10.2.2 The 50.2 Hz risk

Originally, almost all PV plants in Germany were designed with a cut-off frequency of 50.2 Hz according to the former standard for generation plants on low voltage grids. Therefore, all PV plants on the low voltage grid would disconnect at 50.2 Hz. With the rising capacity of solar power in the German low voltage grid, this became a severe risk for the overall power system. Even though events with over frequencies of 50.2 Hz are very rare, the European power system was not designed to handle the cut-off of up to 12.7 GW, which was the installed capacity of solar power on the low voltage grid with the particular setting in 2010 (Boemer et al (2011). As a response to this risk, more than 300,000 PV installations were retrofitted with new control standards, implementing either dispersed settings for cut-off frequencies or linear reduction of output as function of the frequency.

10.2.3 Grid codes

As is the case for wind power, grid codes are an important measure to ensure grid friendly generators. Both voltage problems due to reverse power flows, as well as the 50.2 Hz risk, could be mitigated by changes to the network codes regarding cut-off behaviour and requirements for reactive power control. Furthermore, larger PV plants can be required to be fitted for remote control.

10.3 Discussion – technical integration issues of solar power in Indonesia

Some of the integration challenges with solar power in Germany were a result of the fast emergence of the relatively untested technology and its characteristics. If solar power is to play a larger role in the Indonesian power system, it is important to assess the infrastructure of the grid at the voltage levels in question, and design the connection codes accordingly. Furthermore, the ability to remote control even smaller units of down to less than 100 kW can improve options for system operation.

10.3.1 References

1. Von Appen et al (2013), Jan von Appen, Martin Braun, Thomas Stetz, Konrad Diwold, and Dominik Geibel, Time in the sun - The challenge of High PV Penetration in the German Electric Grid, ieee power & energy magazine February 2013
2. Sweco, Ecofys, Tractebel Engineering and PWC (2015) Study on the effective integration of Distributed Energy Resources for providing flexibility to the electricity system – A report to the European Commission
3. Boemer et al. (2011) Jens. C. Boemer, Karsten Burges, Pavel Zolotarev, Joachim Lehner, Patrick Wajant, Markus Fürst, Rainer Brohm, Thomas Kumm, Overview of German Grid Issues and Retrofit of Photovoltaic Power Plants in Germany for the Prevention of Frequency Stability Problems in Abnormal System Conditions of the ENTSO-E Region Continental Europe, 1st International Workshop on Integration of Solar Power into Power Systems, 24 October 2011, Aarhus, Denmark

11 Island systems

The Danish power system is interconnected with the large power systems of the Nordic countries to the North and East, and to the continental European systems in the south. As outlined in the previous chapters, this is an important enabler for the integration of variable renewable energy, and thus not all experiences are directly relevant to the especially many small isolated power systems in Indonesia. However, Denmark has some experience with smaller isolated systems as well. One prominent example is the Faroe Islands, which comprises a number of small Islands, whose power system is partly interconnected, but isolated from larger power grids due to the remote location in the Northern Sea (see section 11.1). The power system has an annual consumption of roughly 315 GWh, with a peak demand around 60 MW. Furthermore, the Island of Bornholm in the Baltic Sea is a smaller system, with an annual demand of around 250 GWh, and a peak demand of roughly 55 MW, and only one interconnection to Sweden. The system operates as an isolated system during failures or maintenance of the transmission line to Sweden. This setup has led to a number of research activities on Bornholm regarding integration of variable renewable energy, as system changes as result of improved technical measures are easier to capture. Under the research programme Ecogrid EU in the period from 2011-2015, and now under the research programme EcoGrid 2.0, various research and demonstration projects, particularly regarding smart grids and demand side flexibility measures, have been, and are, carried out.[10]

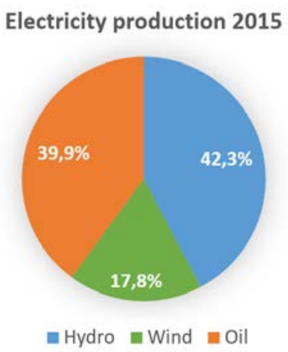
Hybrid systems with generation from e.g. solar PV, wind, hydro and diesel for smaller Islands worldwide is a research topic followed by e.g. the International Renewable Energy Agency (IRENA) as part of the small island developing states initiative (SIDS) and the Global Renewable Energy Islands Network (GREIN). Some Danish technology providers deliver solutions for these kinds of systems (see section 11.2).

11.1 Case story – The Faroe Islands

The Faroe Islands are a small group of islands in the North Atlantic Sea located between Scotland and Iceland. Due to its remote location combined with the small population of only 49,000, the electricity grid is very vulnerable. Overseas transmission is not an option and carbon-based fuels need to be imported, so local renewable generation is the preferred supply option. Relying on fluctuating renewable electricity generation leads to bigger challenges in a small isolated grid compared to the larger and very well connected power system of Denmark. However, the small scale also makes the grid ideal for real life test runs of new technologies. A relatively small adjustment can have a great impact on the grid, and this is one of the key factors that lead to the Faroe Islands having a renewable generation fraction of 60% for 2015.

Hydropower accounts for over 40% of the electricity production, but it is a limited resource, so integration of onshore wind power is a priority. Currently wind power accounts for around 18% of electricity generation and the remaining 40% of the electricity generation is based on diesel generators.

[10] For more information see: /www.ecogrid.dk/en/home_uk, www.eu-ecogrid.net/ and www.PowerLab.dk



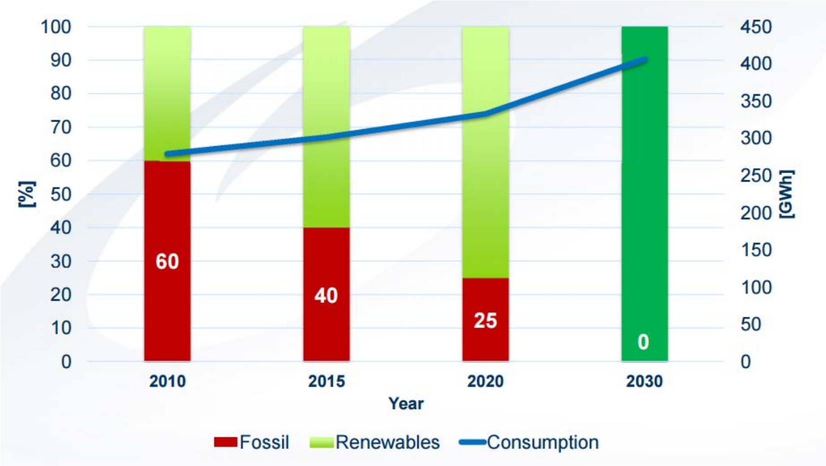


Figure 11-1: Current and future share between fossil based and renewable electricity generation on the Faroe Islands.

11.1.1 The Faroese sustainable energy goals

The Faroe Islands have ambitious goals for the electricity sector both due to the current dependence on imported energy inputs with fluctuating prices, and due to environmental concerns. The original target for 2015 of 55% renewable energy was exceeded with a share of 60% renewable energy. For 2030, an ambitious target of 100% power generation from renewables has been set. Wind power will play an important role in reaching the target, as the wind potential is large. However, stabilisation problems need to be addressed in order to utilise this energy source.

The main measures for integration of wind power on the Faroe Islands are

- Flexible use of hydro power
- Flexible generation diesel generators
- Wind turbine control
- Electricity storage
- Demand side management (Power Hub)

11.1.2 The power system

The Faroe Islands is made up of 18 islands whereof 17 are populated. Five of the islands are not connected to the main grid but have small local diesel generators. The total land area of the Faroe Islands is around 1,399 km² and the longest distance between neighbouring islands is around 8 km. The electricity consumption is expected to increase by 2%-4.5% per year due to growing industry and increased consumption for electric heating (heat pumps) replacing oil burners, and increased consumption of electricity for transportation in the longer term.

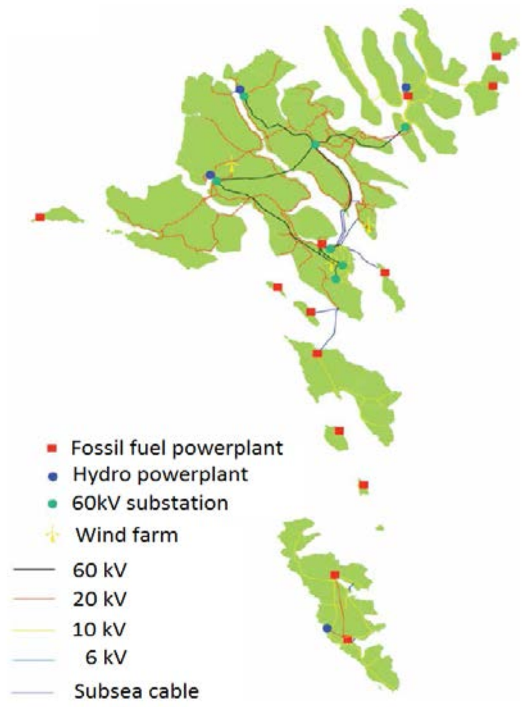


Figure 11-2: The electricity grid connecting 12 of the 18 islands in the Faroe Islands

SEV is the main power company owned by the Faroese municipalities, and acts as both generator and a grid operator (transmission and distribution) responsible for balancing the power supply at all times. There is one other wind company on the market, Røkt, but its share is very small. A fixed electricity price is determined politically, and any new energy project is put out to tender so all interested companies can make an offer.

Key figures in the Faroese electricity supply

- Consumption per year 314.4 GWh (2015)
- Generation shares:
  - Thermal: 125.5 GWh
  - Hydro: 133.1 GWh
  - Wind: 55.8 GWh
- Expected increase in consumption per year: 4.5%
- Peak demand: ~ 60 MW
- Electricity price: ~ 1.71 DKK/kWh (dependant on yearly consumption. Industrial consumers pay less, households pay more)
- 2016-2020: 682 million DKK investments in grid development.
- 12 grid connected islands with a total of 1778 km of cables.
- 25,738 tonnes heavy oil used in generation in 2015.
- Emissions for 2015: 99,619 tons CO_2
- Specific CO_2: 326 g/kWh

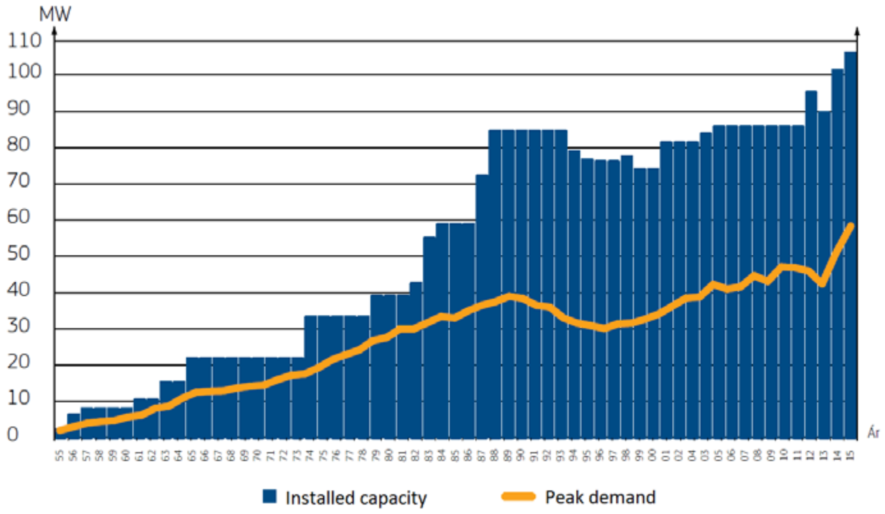


Figure 11-3: Installed capacity and peak demand in the Faroese main grid in the period 1955-2015.

The high shares of wind power are mainly balanced using both hydro power and adjustment of the diesel generator. An example of generation patterns for a period of two days is shown on Figure 11-4. Other measures for stable operation of the power system include a battery system (section 11.1.5), and advanced load management (section 11.1.6).

Figure 11-4: Balanced grid operation for two days in September 2014. The wind generation is mainly balanced by hydro power in this specific period, but hydro is limited so the diesel generation is also utilized.

11.1.3 Hydropower

SEV currently has six operating hydroelectric power plants of varying sizes and they produce roughly 40% of the total electricity production. The Faroese hydro reservoirs have storage capacities corresponding to a few days of generation. Combined with sufficient capacity, hydropower is able to increase its generation by 5-6 times compared to normal operation, thereby contributing to ensuring grid stability. The challenges concerning hydropower in the Faroe Islands are linked to low precipitation in the summer, and environmental considerations (empty rivers, wildlife, and appearance).

11.1.4 Wind power

Wind power production on the Faroe Islands started with the first wind turbine being erected in 1993. The latest addition to the onshore wind power production is the wind farm in Húsahaga that started its production in October of 2014. The cost of the wind farm was about DKK 85 million for 13 wind turbines with a combined production capacity of 11.7 MW. The project will raise the percentage of wind power in the system from 8% to 23%. The other wind production units are five 900 kW wind turbines in Neshagi (SEV), and three 660 kW turbines in Vestmanna (Røkt). In 2015, the electricity production from wind was 55.8 GWh, equivalent to 17.8% of the total production, but this fraction is expected to increase as a battery system is introduced in 2016.

11.1.5 Battery system

A collaboration between SEV, ENERCON and Saft has led to the development of Europe's first commercially deployed lithium-ion energy storage system (ESS) connected to a wind farm. The Li-ion battery has a nominal rating of 0.7 MWh and 2.3 MW, and operates in combination with the 12 MW wind farm in Húsahaga. The battery was put online in May of 2016, and will allow for more wind energy utilisation from the connected wind farm. The ESS is expected to provide storage to stabilise generation from milliseconds to several minutes. As such, the ESS will smooth ramp up/down rates as well as provide frequency response and voltage control. The cost of the ESS is approximately 15 million DKK.

11.1.6 Power Hub

Another attempt to balance the fluctuating supply was with the world's first full scale smart grid electricity system, Power Hub. The system was developed by DONG Energy and was tested and installed in the Faroe Islands in 2012. Power Hub monitors the grid and provides load management by disconnecting selected industrial loads which can tolerate a power shortage for a limited amount of time. This gives SEV time to adjust generation and bring the system back in balance. The units that can be disconnected are either heat pumps or cooling compressors thus allowing for demand flexibility due to the heat/cooling storage properties. The system has proven successful as 2-3 blackouts are now avoided on a yearly basis. The project is part of an EU funded research project lead by DONG Energy, but SEV is planning to continue and extend the project in the Faroe Islands as the research project expires.

11.1.7 Future objectives

In the coalition agreement from the Faroese government it is stated that in 2030 all electricity production on land should come from renewable energy sources. However, it is not specified how this target will be reached, because as Hákun Djurhuus, CEO of SEV, points out, the technology does not exist yet, so the goal is dependent on the continuous technological development of renewable energy. Besides the integration measures mentioned in the previous sections, the options for pumped hydro storage are under evaluation.

Apart from wind power, tidal energy is considered as an option due to the available resource in straits between the 18 islands, seen in (Figure 11-5). Tidal energy is predictable over a longer time horizon, reducing the integration challenge.

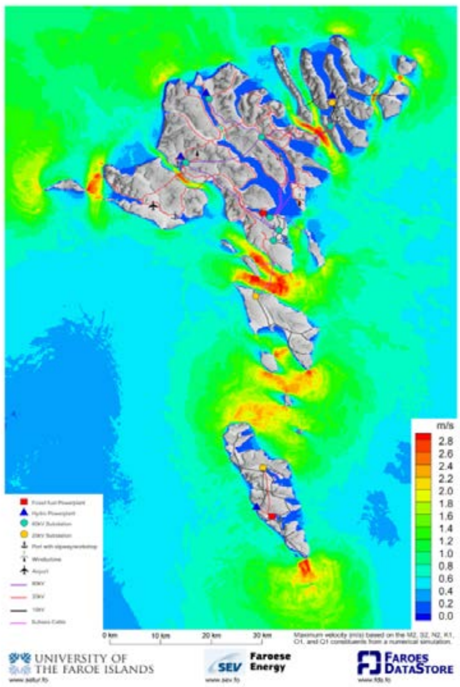


Figure 11-5: Straits with high currents exist between many of the islands and the potential generation peaks are shifted in time relative to each other.

11.1.8 References

1. Terji Nielsen (2014) Integrering af vind på Færøerne, presentation at "Net temadag om fremtidens elsystem, December 2014"
2. SEV (2016), Ársfrágreiðing og Ársroknskapur 2015, Ársaðalfundur 29. Apríl 2016
3. SEV (2016), Framleiðsluroknskapur 2015, Ársaðalfundur 29. Apríl 2016
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8. Faroese Ministry of Trade and Industry (2015), Action Plan - Report and Recommendations on the future electric energy system of the Faroe Islands
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11.2 Case story – Micro-grid solutions for remote islands and villages

11.2.1 Some examples and cases

Technologies for substituting expensive and polluting diesel generation in remote areas and on islands are areas of particular attention globally.

In addition to the case from the Faroe Islands, a number of other cases are known.

These are referenced below, including links.

Case	Link
Tasmania: Hybrid system (Wind, Solar, Battery, Diesel)	http://www.kingislandrenewableenergy.com.au/ http://www.hydro.com.au/system/files/documents/Hybrid_off-grid_solutions/HydroTasmania_Hybrid_Off_Grid_Solutions_CaseStudy_FlindersIsland.pdf
Tokelau: Hybrid System (Solar, Batteries)	http://www.sma.de/en/newsroom/current-news/news-details/news/3943-tokelau-becomes-the-worlds-first-100-solar-powered-country.html https://www.sma.de/en/industrial-systems/hybrid.html
Various Hybrid Cases (Solar, Storage)	http://www.australianenergystorage.com.au/site/wp-content/uploads/2015/06/Simon-Franklin.pdf