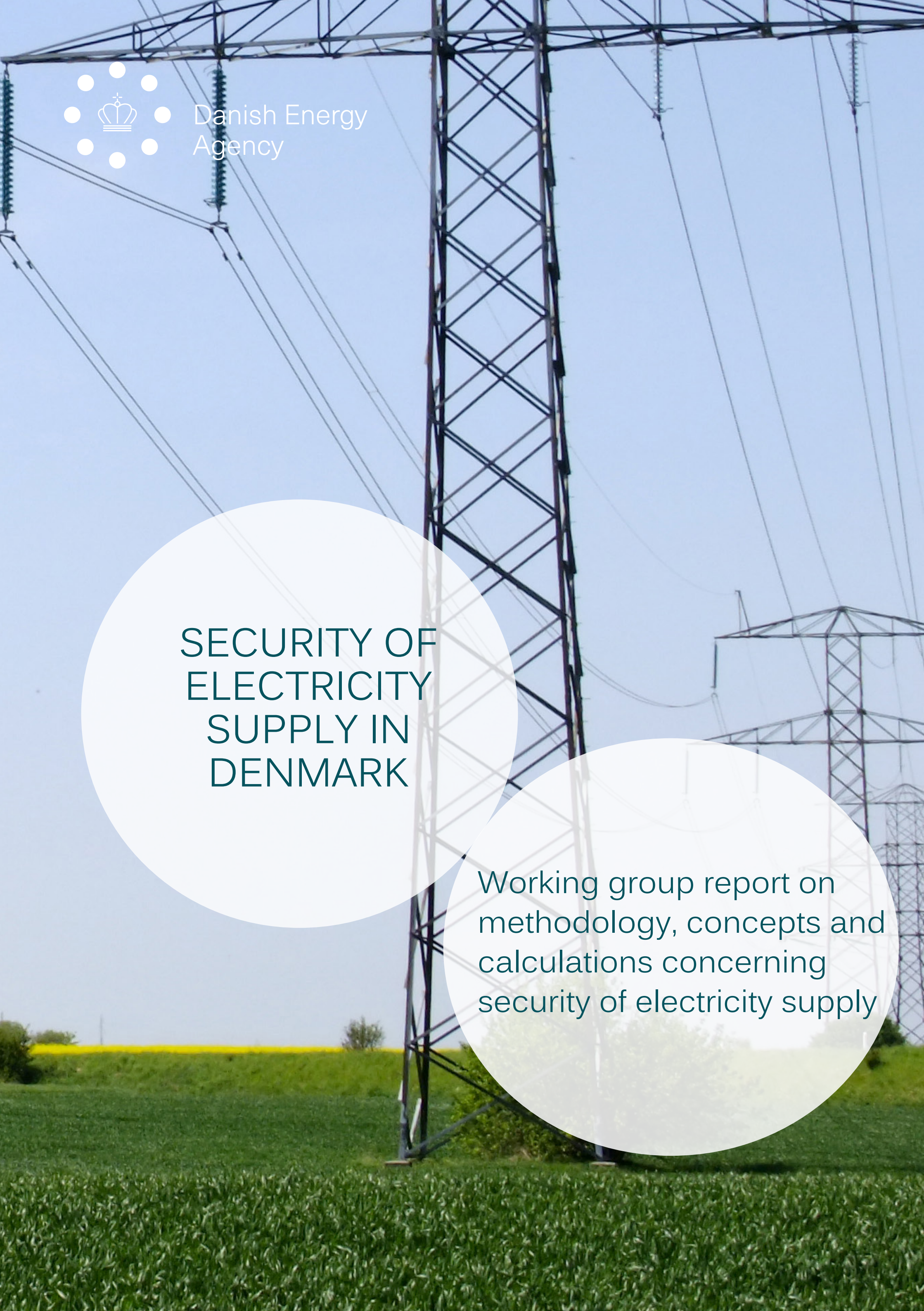
Danish Energy Agency



SECURITY OF ELECTRICITY SUPPLY IN DENMARK

Working group report on methodology, concepts and calculations concerning security of electricity supply

Contents

PROJECT PARTICIPANTS:

The Danish Energy Agency (chairman)
The Danish Energy Association
The Danish District Heating Association
The Confederation of Danish Industry
The Danish Wind Turbine Owners' Association
Energinet.dk
The Danish Consumer Council
The Danish Agriculture & Food Council
The Danish Wind Industry Association (DWIA)

Summary

The Danish electricity system is in a period of rapid transformation. Increasing deployment of renewable energy and interconnections to countries with different production technologies and demand patterns will lead to a Danish electricity system that is significantly different from today. With new interconnectors, Denmark will increasingly become part of a regional, rather than a national, electricity system. Similar developments are taking place in Denmark's neighbouring countries. In March 2015 the European Council endorsed a plan for an Energy Union, which aims at increased regional collaboration on security of electricity supply.

Security of supply is defined as "**the probability that electricity is available when demanded by consumers**". Security of electricity supply in Denmark today is at 99.99%. Seen over a period of several years, this corresponds to an average consumer being without electricity for around 40 minutes a year. The large majority of power supply interruptions in Denmark arise in the distribution grid. There has never been a power failure due to a shortage of electricity generation capacity in Denmark.

In an international perspective, Denmark has a high degree of security of supply. This is due, in particular, to the extensive undergrounding of low and medium voltage power lines over the past decade. This has made the distribution grid more robust with regards to storms etc.

Security of supply is divided into three levels. The distribution grid is by far the greatest source of interruptions. At transmission level, a distinction is made between system adequacy and system security. System adequacy is a measure of the plant, power lines and interconnectors available in the system. System security is a measure of how robust the power system is with regards to failures. Energinet.dk has overall responsibility for maintaining security of supply in Denmark.

In recent years the debate on security of supply has shifted focus from undergrounding of overhead power lines to ensuring a reliable electricity supply in a green transition. The increasing share of renewable energy has not affected the level of security of supply in Denmark. In future, however, it will be necessary to ensure that capacity adequacy forecasts take account of the role of wind power in electricity supply, and that these forecasts take account of the development of new interconnectors.

The project had three main priorities:

1. Reaching a common understanding of security of electricity supply and how to estimate security of electricity supply based on the 2014 Danish Energy Agency report: "The electricity grid - an analysis of the functioning of the Danish power system "

2. Updating the status for capacity adequacy up to 2025;

3. Performing an analysis of the costs of scheduled and unscheduled power outages for different consumer groups.

In January 2015, the Danish Energy Agency initiated a project to find common ground for an overall framework for security of the electricity supply in Denmark, as well as updating the results of the report: "**The electricity grid - an analysis of the functioning of the Danish power system**". Key stakeholders in the electricity sector were invited to take part in the project.

Reaching an understanding of security of electricity supply and estimating security of electricity supply

The project participants agreed on a number of recommendations on the development of capacity adequacy forecasts, on capacity adequacy reporting, and on the status of security of supply.11
There are five overarching recommendations for developing forecasts for capacity adequacy.

1. **A probabilistic methodology be used in capacity adequacy forecasts**
Historically, capacity adequacy has been assessed using capacity balances, where the sum of the number of MWs from thermal generation plants is compared to the maximum demand. This methodology no longer provides a true picture of the risks facing the system as it cannot capture the value of variable generation from wind and solar resources. A probabilistic approach that can effectively include more variables in adequacy calculations provides a more realistic picture of system adequacy.

2. **Capacity adequacy is reported as the frequency of expected capacity shortfalls and expected unserved energy**
A probabilistic approach to capacity adequacy calculates the risk of capacity shortages in a given period (LOLP; Loss-Of-Load-Probability) and the expected amount of unserved energy (EUE; Expected Unserved Energy).

3. **When preparing capacity adequacy forecasts, assumptions should be supplemented with a number of sensitivity analyses to highlight the impact of changes in the most important data assumptions related to securing capacity adequacy in the future**
The assumptions applied in analyses of capacity adequacy have considerable bearing on the results. As there is a degree of uncertainty associated with assumptions, it is important to add sensitivity analyses that reflect the most important uncertainties.

4. **Capacity adequacy forecasts should, as far as practically possible, be prepared in compliance with the requirements for capacity adequacy reporting by which Denmark is obligated internationally.**
International organisations such as ENTSO-E and the Energy Union are considering preparing a common methodology based on a probabilistic methodology for estimating capacity adequacy. Where appropriate, future capacity adequacy forecasts should be prepared so that they comply with international methodologies.

5. **Flexible pricing programmes should be included in capacity adequacy forecasts where possible**
The project participants recommend that flexible pricing be included in capacity adequacy forecasts and compared to alternative models for achieving the desired level of security of supply, when there is sufficient knowledge and data about the potential for flexible pricing.

Participants in the project agree on the following recommendations for reporting security of electricity supply:

6. **Outage statistics should include the reason for each outage, should reflect a period of more than ten years and should show the length of outages caused by lack of capacity.**
The objective of this is to provide greater transparency about the development of capacity adequacy over time and to contribute to fine-tuning the methodology and the model.

7. **Energinet.dk should include relevant security of supply indicators in reporting security of electricity supply.**
Reporting should indicate whether minor or major interventions in market mechanisms have been necessary in order to balance supply and demand.
With regard to further work on security of electricity supply, the stakeholders agree on the following recommendations:

8. **A technical forum will be established to continue discussions on security of supply and developing the methodology for calculating capacity adequacy**
The methodology used for forecasting capacity adequacy should be subject to continuous development. The stakeholders have agreed that they want to continue collaborating on technical aspects of developing capacity adequacy forecasts in a less formal structure than applied for this project.

9. **Recommendations pertaining to work on revising the EU Electricity Security of Supply Directive**
The European Commission will prepare a European methodology for assessing capacity adequacy in Member States as part of the upcoming revision of the Directive on Electricity Security of Supply Recommendations from the project should serve as input for Denmark's negotiating position.

10. **The recommendations are technical input for developing legislation for annual reporting on security of supply as recommended by the Danish Electricity Regulation Committee[1]**
The Danish Electricity Regulation Committee suggested that Energinet.dk prepare an annual security of electricity supply report for the Danish Minister for Energy, Utilities and Climate, describing the status of security of electricity supply and presenting prognoses for the next ten years. Recommendations from this project should form the basis for developing legislation for annual reporting on security of electricity supply

Capacity adequacy status up to 2025

Capacity adequacy in Denmark has been assessed in this project. Two assessments were carried out. One assessment using national calculations and one using regional calculations that included countries with which Denmark has interconnectors[2]. The results are as follows:

1. Estimated capacity adequacy today is good, which is consistent with the fact that no electricity shortages have been observed in recent times.

2. The Danish electricity system's dependence on neighbouring countries will grow over time. This is not a problem in itself, but it will become more important to secure the availability of interconnectors and the capacity that these provide. Denmark will have

more capacity through interconnectors in 2020 than the maximum Danish electricity demand and, in this respect, will therefore be better positioned than its neighbouring countries.

3. The national calculation includes situations with capacity shortages in DK2 (East Denmark) throughout the period. However, the rate of capacity shortages will not be significant until after 2020.

4. Among other things, these calculations suggest that the time lags between neighbouring countries with regard to electricity demand, wind power generation and photovoltaic power generation provide ample opportunity to 'share security of supply'.

Analysis of the costs of scheduled and unscheduled power outages for different consumer groups

DAMVAD has prepared an external consultancy analysis of the costs of scheduled and unscheduled power interruptions for different consumer groups. The objective of the analysis was to facilitate a better understanding of how demand can contribute to security of supply.

The analysis indicates that all consumers can minimise costs incurred from power outages if they are given prior warning, and that costs vary between consumer groups and depend on the length and time of the outage. The analysis reveals median costs of outages of between DKK 22 and DKK 276 per kWh for a four-hour outage. The costs are highest for industry and the service sector and lowest for households and agriculture. Methodologically, it is difficult to determine the costs of supply disruptions for consumers, and the analysis results should therefore be interpreted with some caution.

1. As part of the energy agreement of 22 March 2012, it was decided to appoint a committee to carry out an in-depth review of the regulation of the Danish electricity supply sector in order to ensure incentives for a green transition taking into account cost efficiency, competition and consumer protection. The committee is headed by an independent chairman and consists of representatives from the energy sector, consumer interests, business organisations and green organisations.

2. The results and the methodology applied are described in the Danish Energy Agency's technical background report "Capacity adequacy calculations using the SISYFOS model", which can be found on the Danish Energy Agency's website, www.ens.dk.

1 Introduction

There will be higher levels of variable generation from wind and solar power in the sustainable power system of the future. This development has already been underway for some years, in particular with regard to the deployment of wind power, while the share of photovoltaic solar modules has increased dramatically in recent years. From an overall perspective, this trend means that electricity generation will be considerably more decentralised in future, as well as less controllable and more dependent on wind and solar conditions. This requires a new approach to operation and planning of the electricity system, including with regard to how capacity adequacy is determined and forecast.

Security of electricity supply will be ensured through a combination of large-scale power plants, small-scale CHP plants, wind power, photovoltaic solar modules, the electricity grid, interconnectors and generation capacity abroad. There is also potential for flexible pricing and consumers volunteering to be curtailed from the grid in exchange for some form of compensation. Efficient system operation will also play a key role in reducing the risk of critical operating situations developing into outages.

Traditionally, the electricity system has been based on thermal power plants. Today variable renewable energy sources and interconnectors also play an important role in the electricity system. The cross-border link to neighbouring countries has increased competition in the electricity market. An increased share of wind and solar power, low coal prices and muted demand has deflated electricity prices in recent years. Consequently, the revenue base for power plants has diminished, reducing incentives to make new investments or reinvest in existing capacity. At the same time, the technical lifetime of existing thermal power plants is eroding and many plants are being decommissioned. This is a trend seen not only in Denmark. Germany is massively expanding its wind and solar capacity, while at the same time decommissioning nuclear power capacity. Sweden is also dramatically expanding its wind capacity.

The national and regional electricity markets in Europe are being integrated to an ever greater extent through international transmission links. In March 2015, the European Council endorsed a plan for an Energy Union. The Energy Union opens up for greater coordination and integration of energy and climate policy at regional and EU level. Among other things, the Energy Union is to pave the way for increased European and regional collaboration on security of electricity supply with a view to more efficient utilisation of power plant capacities across national borders. As a result, the individual country will be able to draw more on its neighbours in shortfall situations. In Europe, Denmark is among the countries with the strongest links to its neighbouring countries, and expansion in this area is ongoing. Danish interconnectors will be of ever increasing importance for securing a reliable electricity supply.

Today, only a very small share of total electricity demand utilise flexible pricing. However, with increased electrification and the installation of smart electricity meters for all end users by 2020, demand is expected to play a more active role in the electricity market and in contributing to capacity adequacy. In the longer term, it is likely that voluntary curtailment from the grid will

contribute to ensuring a reliable supply of electricity.
The grid will also play a pivotal role for security of electricity supply. The Danish electricity grid is very robust. Large parts of the low and medium voltage grid have been cabled and this will continue in the future. Overhead to cable conversion of the grid means that storms no longer pose a major risk to security of supply.

THE OBJECTIVE OF THE PROJECT

In January 2015, the Danish Energy Agency instigated a project to find common ground for an overall framework for security of electricity supply in Denmark and update the prognoses for security of supply towards 2025. Key stakeholders in the energy-sector were invited to take part in the project.

The project had three objectives:

1. Reaching a common understanding of security of electricity supply and the methodology used to develop prognoses for assessing security of supply

2. Updating capacity adequacy status towards 2025;

3. Completing an analysis of the costs of scheduled and unscheduled power outages for different consumer groups

The first objective was to establish a common understanding of how capacity adequacy contributes to security of electricity supply, and to establish a common understanding of the future methodology for developing prognoses for security of electricity supply. The results will form the future framework for assessing and reporting on security of electricity supply. Focus was on the overall methodology and assumptions applied in forecasts, as well as on indicators used in security of electricity supply reporting.

The second objective of the project was to update the capacity adequacy status on the basis of the assumptions agreed upon by the project participants. Updated capacity adequacy forecasts have been prepared for 2015, 2020 and 2025. Calculations have been made for Denmark alone as well as regional calculations covering Denmark, Norway, Sweden, Finland, Germany, the Netherlands and the United Kingdom, i.e. countries with which Denmark is linked, or can be linked, in terms of exchange of electricity.

The objective of the third task was to examine the costs of power outages for different consumer groups, as well as whether warning consumers of power outages affects the expected costs of the supply disruption. The definition of security of electricity supply makes it possible to include contributions to capacity adequacy from consumers accepting flexible pricing programmes. Existing knowledge about the willingness of different consumers to have their power curtailed is limited. This includes knowledge about what consumers would require as financial compensation for being curtailed.

ORGANISATION AND STAKEHOLDER INVOLVEMENT

Project organisation comprised a steering committee that guided the process and a working group that carried out the analytical work and reporting. The steering committee and the working group were both headed by the Danish Energy Agency.

The following organisations participated in both the working group and the steering committee:

- The Danish Energy Agency (chair)
- The Danish Energy Association
- The Danish District Heating Association
- The Confederation of Danish Industry
- The Danish Wind Turbine Owners' Association
- Energinet.dk
- The Danish Consumer Council
- The Danish Agriculture & Food Council
- The Danish Wind Industry Association (DWIA)

During the first six months of 2015, the steering committee held three meetings and the working group held six.

THE STRUCTURE OF THE REPORT

The main report is structured in the following way:

CHAPTER 2

- Background regarding security of electricity supply

This chapter describes the framework for security of electricity supply, and how the central concepts of security of supply are understood by the project participants. The chapter includes the historical level of security of supply, how responsibility for security of supply is allocated by Danish legislation as well as an account of operation of the Danish electricity system. The chapter also describes the Danish electricity system, the interplay between power plants, wind and solar power, the electricity grid, interconnectors and demand, and how the Danish electricity system enters into the larger regional electricity systems in Central Europe and the Nordic countries.

CHAPTER 3

- Capacity adequacy in Denmark up to 2025

The chapter describes the results of the analysis of capacity adequacy in Denmark up to 2025, and how capacity adequacy is estimated by completing probability calculations within the Danish Energy Agency's model, SISYFOS. The key findings from a number of sensitivity analyses are also described.

CHAPTER 4

- The results from DAMVAD's analysis of consumer costs in connection with scheduled and unscheduled power outages

This chapter consists of discussion by project participants on the results from DAMVAD's analysis and makes suggestions of further analyses in view of the results in DAMVAD's report. The chapter furthermore contains a summary of DAMVAD's results and conclusions.

CHAPTER 5

— Recommendations

This chapter describes the recommendations agreed by the project participants during the course of the project as well as follow-up of the work in the project.

APPENDIX

- Project participants

The appendix lists the project participants.

2 Background

THE DANISH ELECTRICITY SYSTEM

The Danish electricity system consists of two non-synchronous areas: West Denmark (DK1) and East Denmark (DK2). West Denmark is part of the European continental electricity system, while East Denmark is part of the Nordic electricity system, which also counts Sweden, Norway and Finland. East and West Denmark are linked by a direct-current link under the Great Belt. In addition to this, the system also comprises:

- The transmission and distribution grid which transports electricity between generation and demand.
- Large-scale CHP plants which generate electricity and add stability to the grid by providing voltage and frequency regulation. The Danish Energy Association
- Small-scale CHP plants which, like the large-scale CHP plants, generate electricity, but which are smaller and are more widely spread throughout the entire electricity system.
- Offshore wind farms, onshore turbines and photovoltaic solar modules which generate large amounts of renewable energy for the electricity system.
- Interconnectors connecting Denmark to the Nordic and Central European electricity systems and which play an important role for electricity trading between the countries.The Danish Agriculture & Food Council
- Flexible pricing programmes and voluntary curtailment from the grid[3], which today play only modest roles but which are expected to play bigger roles in the future.

The electricity grid is divided into two levels, the transmission grid and the distribution grid. The transmission grid, which is owned by Energinet.dk, is the grid's super highway, while the distribution grid is the minor roads which transport electricity over the final stretch to consumers and which is owned by the grid companies.

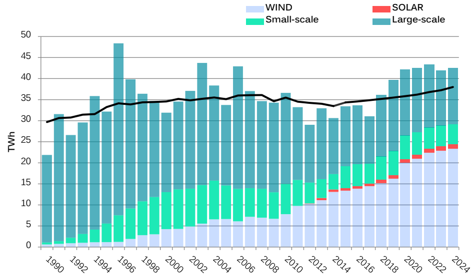
The Danish transmission grid is linked to foreign countries via six electricity links. This links are to Sweden, Norway and Germany and they are regulated jointly by Energinet.dk and the system operator in the relevant country. Figure 1 shows Denmark's current interconnectors, approved links as well as links under consideration. The COBRA link to the Netherlands has been approved, while the Viking link to the United Kingdom is under consideration.

The large-scale CHP plants are thermal plants that run on fuels such as coal, natural gas or biomass. Generation by these plants is regulated according to demand, and the majority of the fossil-fuelled plants can also be run in condensing operation mode, i.e. generating electricity without producing district heating. Condensing operation allows for greater flexibility in the electricity system, in particular in the summer when the demand for heating is low. The large-scale CHP plants are connected to the transmission grid and provide system stabilising properties such as inertia, reactive effect, etc. and thereby maintain the stability of the grid.

3. Flexible pricing programmes refer to demand that is price-sensitive and which acts on price signals in the spot market. Voluntary curtailment from the grid refers to when consumers, possibly in return for pre-agreed compensation, are curtailed from the grid in order to reduce demand in the system in periods of scarcity.

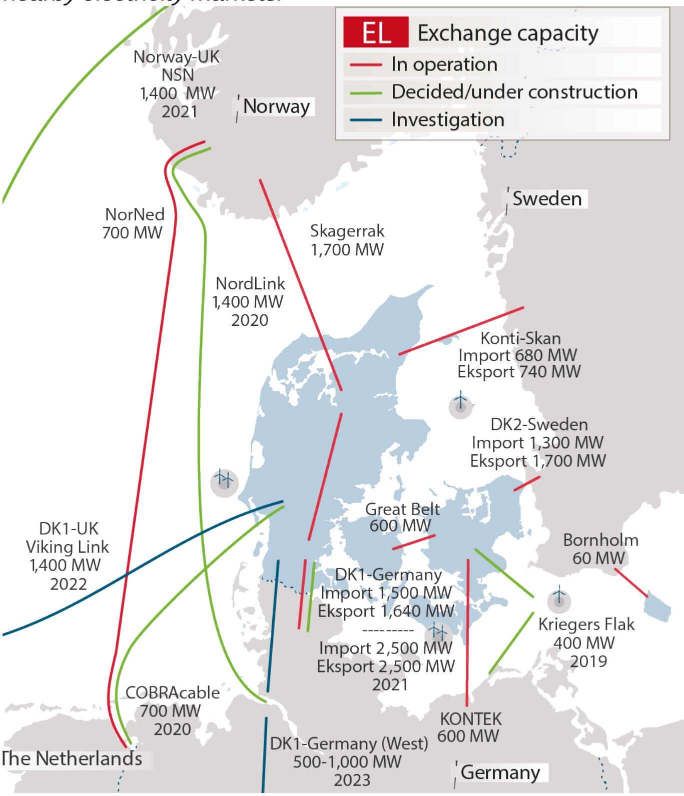
The small-scale CHP plants are thermal plants connected at medium and low voltage levels that typically cannot generate electricity without generating district heating simultaneously. Usually, small-scale CHP plants are somewhat smaller than the large-scale CHP plants. Offshore turbines, onshore turbines and photovoltaic solar modules are variable generation plants, i.e. they generate power in windy or sunny conditions, respectively. It is difficult to predict accurately how much electricity an individual turbine will generate in normal wind conditions. However, if we look at total generation by many wind turbines across a larger geographical area such as Jutland, predictability improves. Although the position of the sun relative to the photovoltaic solar modules is entirely predictable, how much electricity the modules produce can be difficult to predict because this depends on cloud cover.

Figure 2: Electricity demand and generation 1990 - 2024.



Source: Energinet.dk

Figure 1: International transmission links between Denmark and nearby electricity markets.



Flexible demand only accounts for a very small share of total electricity demand today. However, in the longer term, it could contribute to ensuring capacity adequacy through voluntary curtailment schemes.

THE DANISH ELECTRICITY SYSTEM IN A REGIONAL CONTEXT

The Danish electricity system is situated between the predominantly hydro- Nordic electricity system and the thermal Central European electricity system. Denmark's strong transmission links to neighbouring countries allows the Danish system to benefit from these different systems, and Denmark plays an important role as a transit country for transport of electricity between the Nordic countries and Central Europe.

Because of its location between a low-price area (Nordic countries) and a high-price area (Central Europe), Denmark has ample opportunity for cross-border trading and is the reason why, compared with other countries in Europe, Denmark is strongly linked to its neighbours. Figure 3 compares Denmark's total transfer capacity over its interconnectors relative to other national electricity systems in 2020. The sum of Denmark's interconnectors exceeds Danish peak-load demand. This contributes to robust capacity adequacy for Denmark.

Because of Denmark's strong electrical interconnection with its neighbours, day-to-day system operation is closely linked to operations in neighbouring countries. Denmark's interconnectors have great value for Denmark. They contribute to cost-effective use of generation capacity through the electricity market in Denmark and abroad and they reduce the costs associated with ensuring an adequate supply of electricity to Danish consumers. Denmark's strong interconnectors also contribute to cost-effective integration of renewables. Caution should therefore be applied in analysing the Danish power system in isolation.

CENTRAL CONCEPTS

Security of electricity supply can be broken down into system adequacy and system security, see Figure 4.

System adequacy refers to the electricity system's ability to meet total demand. System adequacy is both capacity adequacy and grid adequacy, where capacity adequacy is the system's ability to produce the right amount of electricity at the right time.

Figure 3: Capacity in interconnectors relative to maximum demand 2020.

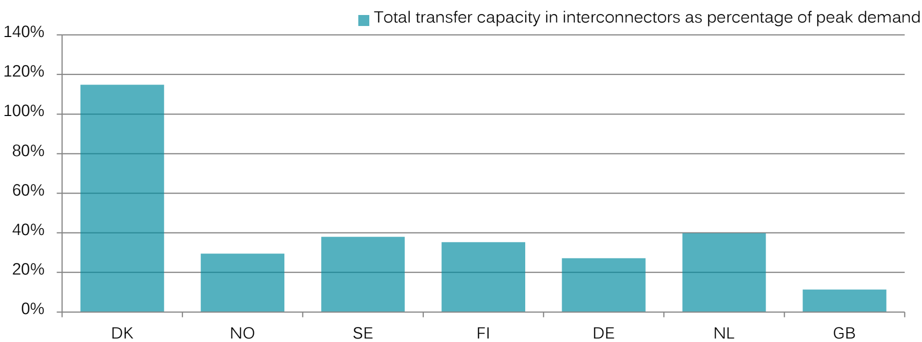
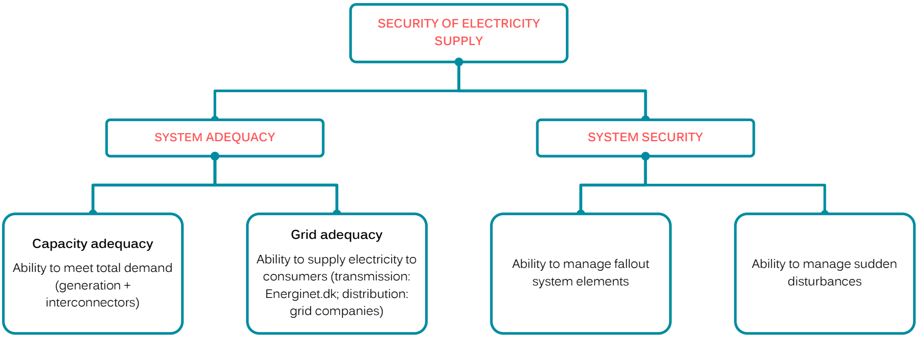


Figure 4: Hierarchical illustration of security of electricity supply.



Grid adequacy is the ability of the transmission and distribution grids to transport the required amount of electricity from the place of production to the place of consumption. Capacity adequacy is ensured by large-scale and small-scale CHP plants, photovoltaics, wind turbines and interconnectors, while transmission adequacy is ensured by a transmission network with adequate transmission capacity. When a lack of system adequacy does occur, this is managed by curtailing consumers in a limited area. This is called a controlled curtailment or brownout. There has been no brownout in Denmark to date.

System security is the ability of the electricity system to manage sudden disturbances in operations caused by e.g. short circuits, or sudden failure of a power plant or a transmission link, without this affecting the power supply or leading to power outages. Disturbances that spread throughout the electricity system because of a lack of system security can close down large parts of the system. System security focuses on preventing this from happening by establishing security mechanisms in components, which can either isolate faults from the rest of the system or prevent uncontrolled power flows by ensuring an alternative route in the electricity grid.

If system security fails, faults can quickly spread through the electricity system, resulting in a cascade effect. Cascade effects happen when a fault in a single component causes the current to flow unchecked to other components in the electricity system. If this leads to faults in one or several other components, causing these to fall out, the overload could quickly propagate to other parts of the system because all components in the electricity system are interconnected. This can lead to a surge of uncontrolled power flows moving through the electricity system and causing faults in components or causing e.g. power plants to disconnect from the system to protect the plant's installations. The ultimate result could be system collapse and a major blackout.

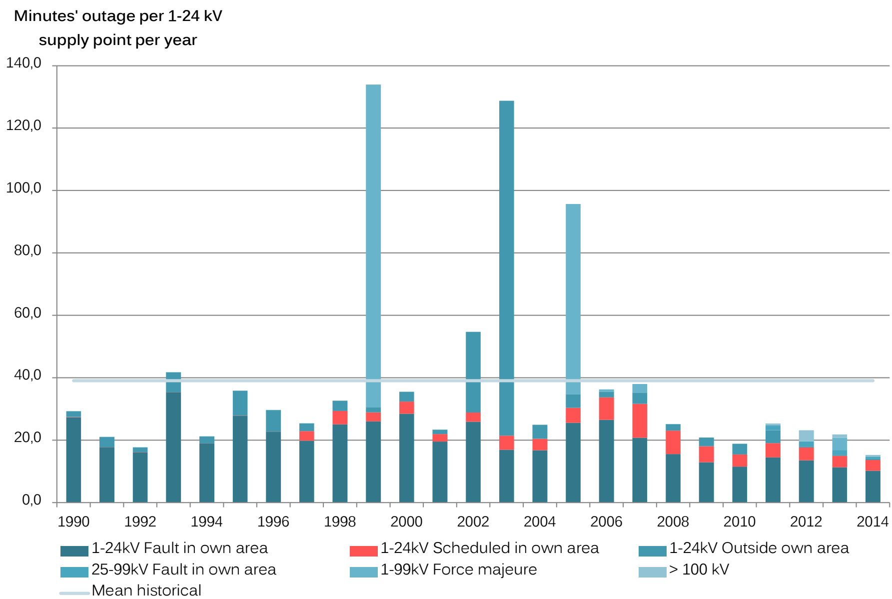
Cascade effects are prevented by establishing system protection that limits the consequences of faults. System protection includes relays which are electrical switches that isolate faults from the remainder of the electricity system. System protection can also be protective measures to ensure adequate ancillary services in the electricity system. Ancillary services help ensure the reliability of the electricity system and are usually provided by large-scale CHP plants or synchronous compensators

In practice, system adequacy and system security are closely related. They are, however, planned for separately, as system adequacy is a static condition which can be predicted with relative certainty, and the effect of which can therefore be reduced. System security, on the other hand, is dynamic, as it concerns sudden incidents which create imbalances in the electricity system and, thus, affect power supply.

HISTORICAL LEVELS OF SECURITY OF ELECTRICITY SUPPLY

Denmark enjoys a high level of security of electricity supply. Since 1967, Danish electricity grid companies and Energinet.dk have prepared statistics of faults and failures in the Danish power supply system through the ELFAS database. Since 1990 Danish security of electricity supply has been at approximately 99.99%. This corresponds to an average consumer being without power for 40 minutes over the course of a single year. The 40 minutes a year is an average figure for all consumers over the period. (See figure 5.) In practice, many consumers never experience an outage during the course of a year, while others experience

Figure 5: Security of supply in Denmark 1990 - 2014.



Source: Danish Energy Association

one to several outages lasting from minutes to hours.

The distribution grid has far more outages than the transmission grid, but outages in the distribution grid usually only affect a few customers, while faults in the overall transmission grid affect many. In figure 5, outages in the distribution grid are stated as 'in own area', while outages caused by faults in the transmission grid are stated as 'outside own area'. Inadequate electricity generation has not contributed to power outages in Denmark since the onset of comprehensive registration of faults in the electricity supply in the 1960s.

Figure 5 illustrates that there have been no major blackouts in Denmark in the past ten years. Undergrounding the distribution grid has played an important role in improving security of supply. The storms in 2013 were equal in strength to the 1999 and 2005 storms. However, as opposed to the two earlier storms, the 2013 storms did not lead to any significant outages. This was mainly due to the fact that overhead lines in the distribution grid had been put underground in the intervening period.

For a true and fair picture, we have to look at security of supply over many years, e.g. 20-25 years. Incidents in the transmission grid which lead to supply failure are very rare but usually have serious implications for supply. If the status for security of electricity supply is not analysed over a longer period, the rare but statistically significant incidents will either be 'invisible' or affect statistical results disproportionally.

Since 1990, Denmark has seen four significant power outages which are reflected in the statistics on security of electricity supply, see box.

RESPONSIBILITY FOR MAINTAINING SECURITY OF ELECTRICITY SUPPLY

The Danish Electricity Supply Act includes various provisions concerning security of electricity supply, and different authorities have been assigned responsibilities and authority related to these provisions. Pursuant to section 27a (1) of the Electricity Supply Act, the system operator, Energinet.dk has overall responsibility for the security of supply. The Act does not define 'security of supply', however, it does state that Energinet.dk is responsible for maintaining technical quality and balance within the overall power supply system, as well as ensuring adequate generation capacity in the system. Furthermore, Energinet.dk is responsible for the overall infrastructure of the system, i.e. transmission grid and interconnectors. Under section 27b of the Act, Energinet.dk can require that approved plant shut-downs be postponed or brought forward with a view to maintaining security of supply and against fair payment.

The Danish Energy Agency also has a number of responsibilities relating to security of supply. These include issuing authorisations to produce electricity to plants with a capacity above 25MW. Such authorisations can set out conditions that, with one-year prior notice and pursuant to section 50(3) of the Electricity Supply Act, the Minister can require electricity generation companies to maintain a pre-determined minimum generation capacity to ensure security of supply. So far, this provision has not been applied. It is also stipulated that the Danish Energy Agency can make decisions as to whether capacity can be preserved, permanently decommissioned or scrapped, cf. sections 11 and 12 of the Electricity Supply Act. Decisions are made after consulting Energinet.dk.

The explanatory notes to section 27d(2) of the Electricity Supply Act describe how the Minister can assess the security of electricity supply and order Energinet.dk to instigate specific measures to ensure this security of supply.

Grid companies are responsible for developing and operating the distribution grids and, thus, they safeguard the physical delivery of power to consumers. The individual grid company has a monopoly on the physical delivery of power to consumers within a given grid area. The Danish Energy Regulatory Authority is responsible for overseeing delivery quality by grid companies.

CAPACITY ADEQUACY AND THE OPERATION OF THE ELECTRICITY SYSTEM

As a general rule, trade in the electricity market ensures balance between supply and demand.

However, although the market has proven effective in balancing the electricity system, there are concerns as to whether the market provides enough incentive to ensure new investments in generation capacity which can help ensure adequate capacity and flexibility when existing plants are taken out of operation. Energinet.dk is leading a project, Market Model 2.0, which analyses the current market model with a view to recommending changes. The project will be completed in autumn 2015. By then a possible follow-up project is to be considered.

MAJOR POWER OUTAGES
since 1990

8 JANUARY 2005
Around 200,000 households across Denmark lost electricity when a storm with hurricane-strength winds hit Denmark. The majority of the power outages were due to the fact that the distribution lines were damaged by fallen trees and flying objects.

23 SEPTEMBER 2003
Along with the southernmost part of Sweden, all of East Denmark was hit by power outages. The primary cause was a double error on a busbar at a switching station in South Sweden, which brought on an outage in four 400kV lines and two units at the nuclear power station in Ringhals. Before this, a power outage had occurred at the nuclear power station in Oskarshamn unit 3. The result was a voltage collapse in South Sweden and East Denmark. In Denmark, the first consumers had electricity after a couple of hours and last after about six hours.

28 DECEMBER 2002
Around a million people in northern and western Jutland were without electricity for up to three hours as a result of two independent errors in the west Danish transmission grid.

3 DECEMBER 1999
Approx. 440,000 households lost electricity in the worst hurricane of the century. The power outages were mainly due to damage to cables in the distribution grid.

ENSURING THE BALANCE
of supply and demand through the Nordic electricity market

THE DAY BEFORE THE OPERATING DAY (the day-ahead market)
Electricity is traded on the spot market the day before it is actually produced and delivered to the consumer (i.e. the operating day). Electricity suppliers and producers trade on the spot market to cover supply and demand for the upcoming 24 hours. Almost 90% of total electricity demand in the Nordic countries is traded here. By no later than 12 noon, electricity suppliers and producers submit their sale and purchase bids for volumes and prices into Nord Pool Spot. By no later than 1 pm, Nord Pool Spot matches all sales and purchase bids, taking into account any constraints in the electricity grid. 24-hourly prices are then calculated for all Nordic countries using a common price calculation algorithm, balancing the system for the subsequent 24 hours.

UP TO THE OPERATING MOMENT (the intraday market)
If expected supply or demand reported to the spot market changes, e.g. due to power plant failure or changes in wind conditions, the stakeholders can trade in the intraday market, Elbas, to achieve supply-demand balance. The intraday market is open from 2 pm until one hour before the operating hour. After this time, Energinet.dk has sole responsibility for balancing the system through a number of system services that adjust production. Energinet.dk maintains balance in the system, e.g. by buying electricity (upward regulation) or selling electricity (downward regulation) in the Regulation Power Market. Furthermore, grid frequency is stabilised by the automatic reserves in the actual operating moment.

THE DAY AFTER THE OPERATING DAY
After completion of the operating day, actual demand and production measurements are collated and compared with the stakeholders' scheduled production and demand. Any imbalances between actual and scheduled demand/production are cleared in the balancing market.

The spot market is the primary instrument used to balance supply and demand from day to day. After the bids and offers to sell or buy electricity in the spot market have been matched, the electricity system is formally in balance for the upcoming day (24 hours). However, the expected supply or demand offered on the spot market cannot always be realised when it is time to physically deliver the electricity. There will be imbalances, e.g. because of incorrect demand or wind power forecasts, or because of plant failures. Incorrect wind power forecasts are the most frequent cause of imbalances in the Danish electricity system. If supply and demand do not correspond, the supply-demand balance in the electricity system is affected, which ultimately could result in outages.

The Regulation Power Market is used to keep the overall electricity system in balance within the operating hour. Regulation power is traded on the Nordic Regulation Power Market. Energinet.dk activates the traded bids as required during the individual operating hour. A marginal hourly price is then set following the same principles as in the spot market. Producers and consumers pay for any imbalances for which they are responsible. Imbalances are cleared after the operating hour.

Energinet.dk establishes agreements with some producers obligating the producers to make manual reserves available. The agreements obligate the producers to submit bids to the Regulation Power Market for a fixed period of time. The producers are compensated for making reserves available. If any of the bids of a producer are activated in the Regulation Power Market, the producer will be paid the market price for the regulation power it delivers. Compensation payment to producers for making power available ensures that there are always enough reserves available to meet demand in situations with plant failure, interconnector failure or incorrect wind power forecasts. Producers can opt out of making capacity available to the Regulation Power Market and, instead, voluntarily submit regulation power bids when they see fit.

In situations posing a threat to the normal operating conditions of the electricity system, Energinet.dk will operate the system in 'heightened alert'. Since June 2010, there have been five such situations in which 'heightened alert' was implemented. The market is suspended during 'heightened alert' situations. The electricity system is instead regulated directly from Energinet.dk's control centre, and grid companies must prepare contingency measures to cope with any major operating disturbance. Furthermore, all scheduled or ongoing work on grid components will be suspended and the grid will be brought into the most secure operation status as quickly as possible. If the situation worsens, emergency operation is implemented. In this situation, operation of the electricity system will be unstable and there will be local/regional/national outages. Denmark has not had an emergency operation situation since 2010.

The October 2013 storm called Allan was a powerful storm, during which record mean and maximum wind gusts were observed. Energinet.dk called a 'heightened alert' situation during the storm, because of the many incidents in the electricity system as the storm passed over Denmark. The storm illustrated how the Danish electricity system is robust toward extreme weather events and serious incidents, although intentional curtailment of a number of Zealand consumers came very close. Curtailing consumers is one of the instruments available to companies like Energinet.dk, but it is rarely deployed. It has not been deployed in the ten years that Energinet.dk has existed.

EUROPEAN AND REGIONAL COLLABORATION TO SECURE A RELIABLE ELECTRICITY SUPPLY

Internationally, there is increased focus on security of electricity supply, including on the value of working together regionally in order to secure a reliable electricity supply.

In March 2015, the European Council endorsed a plan for an Energy Union based on three overarching principles: a reliable energy supply, sustainability and competitiveness.

Further to these overarching principles, the Energy Union emphasises five elements: 1) security of supply, 2) implementing the internal energy market, 3) increasing energy efficiency, 4) reducing CO_2 emissions, and 5) promoting research and innovation.

Specifically, the European Commission will present a proposal for a new electricity market design to improve security of supply and underpin transformation of the power

STORM ALLAN— Storm Allan put severe pressure on the electrical system in October 2013. A number of critical events occurred during the storm:

12.50
The storm is westerly, and at around 12.50 pm the large wind farms in the North Sea stop producing electricity. When the wind becomes too strong, the turbines stop so that they are not damaged when the blade rotate too fast. This is in itself not that unusual and it is something the electricity grid is used to coping with.

1.57
Energinet.dk's control room receives the first reports about faults in the overall electricity grid. Several towns briefly lose electricity. The first major fault on the electricity grid occurs when a 400kV high-voltage electricity line between Kassø in Southern Jutland and Revsing, a town close to the city of Vejen, cuts out. The curtailment is caused by an electrical short circuit, which may have been brought on by a flying object such as a trampoline, or by two phases being too close. The electricity line is part of the spine of the Jutland-Funen electricity grid and it has great importance in determining how much electricity can be imported to, and exported from Germany. The line is now out, and combined with the fury of the storm, this results in 'heightened alert' from Energinet.dk.

2.41
One of the two 400kV high-voltage electricity lines between Denmark and Germany cuts out because of storm damage in Germany around 30 kilometres from the Danish border. If the other 400kV line cuts out too, the countries will only be linked by 220kV lines. For this reason, all backup facilities in Jutland are on standby so the balance can be sustained, should further storm damage in the transmission grid occur.

3.42 PM
A 150kV transformer curtails in Fraugde in eastern Funen, when an internal error in the transformer occurs. The transformer is vital for the Great Belt electricity connection, and this also cuts out. At that time, the electricity was being transported from east to west. This means an increased strain on the grid in West Denmark. The import from Norway is therefore increased so that the electricity grid remains balanced if the other 400kV line to Germany should be cut-off by the storm. The maintenance staff in Jutland cannot reach the transformer because of an accident on the bridge over the Little Belt. At about 4.20 pm the wind force drops in the North Sea and the offshore wind turbines start producing electricity again. This eases the strain on the west Danish electricity system.

4.21
The 132kV line between Allerød and Stasevang in Northern Zealand is hit by a fallen tree. This starts a cascade effect where both the connection between Zealand and Germany and the large back-up electric power plant on Zealand, Kyndby, cut out.

5.00
The large offshore wind farms at Nysted and Rødsand are shut down because of the force of the wind and the Zealand electricity grid is no longer capable of handling and more major faults. To prevent a potential system collapse, controlled curtailment of 500,000 Zealand consumers is prepared. DONG Energy and SEAS-NVE are asked to stand by to curtail 250MW each, if needed.

5.25
Energinet.dk arrives at the station in Fraugde and the Great Belt connection returns to normal. Electricity can run from West Denmark towards the east, which means that the situation is no longer so serious, and Energinet.dk can call off the 'heightened alert' early in the evening, when operations can return to normal.

DIRECTIVE
on security of electricity supply

Directive 2005/89/EC of the European Parliament and of the Council concerning measures to safeguard security of electricity supply and infrastructure investment was adopted in 2006.

This Directive obligates Member States to ensure the establishment of minimum standards and requirements for the operational stability of the electricity grid. Furthermore, Member States are to take appropriate measures to maintain a balance between supply and demand in the electricity system. Member States are also obligated to include security of electricity supply and investment plans in their mandatory bi-annual report to the European Commission pursuant to the Electricity Directive (Article 4 of Directive 2009/72/EC).

system. Initially, the European Commission is expected to present a consultation paper in summer 2015, describing different proposals for a European market design. The aim is to propose new legislation in 2016. It is likely that the European Commission will focus firstly on regional solutions as a precursor for a common-European solution, so as to ensure greater progress in the development of the market.

In continuation of the market-design focus, the European Commission is expected to present a proposal for a revision of the Directive concerning measures to safeguard security of electricity supply and infrastructure investment in 2016. Among other things, the European Commission is expected to establish acceptable risk levels for supply disruptions, as well as prepare a common methodology for how to assess security of supply; a methodology which will include the issue of available generation capacity. At present, the methodology used to estimate security of electricity supply varies considerably between Member States. The European Commission intends to develop a methodology that takes account of cross-border power exchange, variability of renewable energy production, demand control, and storage capacities.

As several of Denmark's neighbouring countries are also in the process of a green transformation of their energy sectors, and because of the significance of other countries for the Danish electricity price, greater regional and European collaboration in the energy area offer both challenges and opportunities for Denmark.

Germany has initiated a series of meetings between 12 neighbouring countries, including Denmark as well as the European Commission, on regional collaboration about the future electricity market. The process headed by Germany is an attempt, in a regional context, to address common challenges regarding capacity, security of supply and cost-effective incorporation of large volumes of renewable energy. In June 2015, as a result of this process, the participants agreed on a joint declaration of intent, covering a number of common principles for future development of the electricity market. An important principle agreed on is internal and external infrastructure development to prevent bottlenecks, and that cross-border trade should be on market terms and should not be limited during situations with capacity shortfall. Furthermore, the participants also agreed to prepare a common methodology for assessing capacity adequacy with a view to preparing common regional capacity adequacy assessments.

The use of probability calculations in capacity adequacy assessments in regional electricity systems is gaining ground in EU Member States. In March 2015, the Pentalateral Energy Forum (PLEF), which comprises TSOs (transmission operators) in Austria, Belgium, France, Germany, Luxembourg, the Netherlands and Switzerland published a common regional capacity adequacy assessment, on the basis of a probabilistic approach, for the years 2015/2016 and 2020/2021. This was the first such analysis at regional level. The work is being used by the European Network of Transmission System Operators for Electricity, ENTSO-E, which is working on a common probabilistic methodology for assessing capacity adequacy that incorporates cross-border capacity sharing.

3 Capacity adequacy in Denmark towards 2025

The Danish Energy Agency developed a capacity adequacy prognosis for capacity adequacy for the period up to 2025. The prognosis is based on a similar analysis from 2014, but using a more detailed data set and modelling capacity in neighbouring countries .

Historically, capacity adequacy has been assessed using capacity balances, where the sum of the number of MWs from different thermal generation plants is compared to the maximum electricity demand using different weighting. Although capacity balances are commonly used internationally, there is increasing recognition that this methodology does not provide a complete picture of capacity adequacy . Probabilistic methodologies are being developed and are being used to an ever greater extent. For example, see the Common Statement by the Ministries in the Pentalateral Energy Forum from 11 March 2015.

This section also evaluates capacity adequacy on the basis of a probabilistic methodology.

Capacity adequacy (the probability of an adequate number of plants and interconnectors) forms part of security of electricity supply (the probability that electricity is available when demanded by consumers).

Calculations have been made for Denmark alone as well as regional calculations covering Denmark, Norway, Sweden, Finland, Germany, the Netherlands and the United Kingdom, i.e. countries with which Denmark is linked, or can be linked, in terms of electricity exchange. In the national calculations, foreign countries are represented as point suppliers. In the regional calculations, countries outside the model with connection to countries in the model are represented as point suppliers

Estimation has been performed on the basis of a set of baseline data as well as a number of sensitivity analyses. Energinet.dk's assumptions for the technical lifetime of the large CHP plants have been used. For small-scale CHP plants, the Danish District Heating Association questionnaire survey has been used . For Danish wind power, photovoltaic solar modules and electricity demand, the 2014 baseline projection of the Danish Energy Agency has been used. For foreign countries, ENTSO-e and Energinet.dk data has been used, as well as data designed on the basis of Platts' database of European power plants.

The Danish Energy Agency's stochastic model, SISYFOS, was used for the calculations. SISYFOS calculates the probability of capacity shortfalls arising in a given hour (LOLP) and the expected unserved energy – (EUE). Both measures of capacity adequacy are converted into number of minutes per year. SISYFOS also calculates the average availability of capacity, dependence on imports and a number of other key indicators. It should be stressed that prognoses such as these always have a degree of uncertainty attached to them as some of the data used is tentative (e.g. assumptions about future plant shutdowns in Denmark and abroad), and secondly there is also a statistical uncertainty in the calculations. Data uncertainty is addressed through sensitivity analyses, whilst statistical uncertainty is mitigated by performing a large number of calculations.

Main conclusion from calculations:

- Capacity adequacy today is good, which is consistent with the fact that no electricity shortages have been observed in recent times.

- The Danish electricity system is in transition with the number of interconnectors increasing, the share of wind and photovoltaic power generation increasing, and less thermal capacity. Denmark's dependence on neighbouring countries is expected to increase over time. This is not a problem in itself, but it will become increasingly important to secure the availability of interconnectors and accurate assessments of the capacity that these provide. Denmark is expected to have more capacity through interconnectors in 2020 than peak demand in the Danish power system, which strengthens capacity adequacy considerably.

- The national calculation shows increased probability of capacity shortages in DK2 (East Denmark) throughout the period considered. However, the probability of capacity shortages will not be significant until after 2020. The rate will be 'significant' when the number of minutes with capacity shortage is not negligible compared with the total number of minutes' outage that is caused by the low-voltage and transmission grid (around 40 minutes/year). The probability of capacity shortages in DK1 (West Denmark) is negligibly low until 2025. Thereafter the probability increases slightly. Capacity shortage has been estimated in minutes in two different ways. LOLP minutes refer to the expected rate of shortages without taking account of the scope of the shortage. EUE minutes estimate the expected occurrence of unserved energy and convert this to minutes, so that, in principle, these minutes can be compared with recorded historical minutes. See table 1.

- The probability of capacity shortages is fairly consistent with the power system function analysis from 2014.

- The probability of capacity shortages occurring in Denmark is smaller in the regional calculations than in the national calculations. Ideally, the national and the regional calculations should give more or less the same probability of capacity shortage in Denmark, providing the data input is correct. This seems to indicate that the probability of neighbouring countries not being able to supply electricity to Denmark has been overestimated in the national calculation. The calculations therefore suggest that the time lapse between neighbouring countries with regard to demand, wind power generation and photovoltaic power generation provide ample opportunity to 'share security of supply'.

- The calculations do not take account of other constraints in interconnectors than purely physical ones. In reality there may be constraints on interconnectors that are market-related rather than physical. Therefore, it could be relevant to apply a more modest assessment of the ability of countries outside Denmark to supply electricity to Denmark.

- It is deemed relevant to continue both regional and national calculations of capacity adequacy, as the two types of calculation can explain different aspects of the security of electricity supply.

- The average capacity reserve (average capacity available in an area relative to the maximum demand) in DK1 is larger than in DK2 for the entire period.

- Capacity shortages do not only occur during peak-load demand and during periods of no or low wind, as is assumed in methodologies using capacity balances. Consequently, traditional capacity balances are not well-suited for describing capacity adequacy in a system with more variables than simply demand.

A number of sensitivity analyses have been performed. The results of these are described in brief here:

- If Denmark's neighbouring countries (Germany, in particular) do not, to some extent, develop their thermal capacity to replace decommissioned nuclear power plants and other thermal power facilities, then the probability of capacity shortage in Germany will increase significantly. This will affect capacity adequacy in the Danish system. Although such a development is unlikely to occur in Germany in practice, it is important to monitor capacity developments in Germany and elsewhere.

- Increased frequency of failures on interconnectors and an increased

Table 1: Calculated capacity shortage (national)

MINUTES/YEAR	2015	2020	2025
DK1	<-0,02	<-0,02	1,3/0,7
DK2	0,27/0,15	3,3/1,5	29/15

Blue figures

Loss of Load Probability (LOLP) converted to number of minutes' capacity shortage per year.

Red figures

Expected unserved energy (EUE) converted to weighted minutes/year.

probability of neighbouring countries not being able to supply electricity to Denmark will dramatically reduce Danish capacity adequacy.

- Closing of the Swedish nuclear power plants, Ringhals 1 and 2, does not appear to have a significant effect on Danish capacity adequacy.

- Faster and more comprehensive decommissioning of small-scale and large-scale thermal plants than assumed in the baseline estimation will reduce capacity adequacy in DK1 and DK2. More so in DK2, and most significantly after 2020.

- An additional Great Belt connection or a link to the United Kingdom, will improve Danish capacity adequacy. However, an additional Great Belt connection will have a much greater positive effect on capacity adequacy as it will alleviate capacity adequacy in DK2 where the need is greatest. This assessment only covers capacity adequacy and no other possible benefits of new connections.

- Wind power contributes to security of supply in Denmark.

- If around 200MW flexible demand were available for activation concurrently it could remove around half of expected capacity shortages in 2025.

4 Analysis of consumer costs in connection with scheduled and unscheduled power outages

External consultants from DAMVAD performed a separate analysis of the costs of scheduled and unscheduled power outages for different consumer groups..

In principle, an improvement in security of supply, e.g. establishing a new interconnector or procuring more reserves, can be assessed by comparing the costs of power outages for society with the costs of improving security of supply. The results of the DAMVAD analysis provide input for such an assessment, but additional analyses are required before any concrete assessments of this kind can be made. The analysis is based on a questionnaire survey of the following consumer groups: households, industry, agriculture and the private service sector. A total of 645 enterprises and 1,001 households participated in the survey.

The analysis examines the direct monetary costs of power outages for consumers. The costs are determined with regard to the duration of the power outage, when during the day, week and year the outage took place, as well as whether or not consumers received prior warning. The DAMVAD analysis therefore gives an indication of the size of costs of different types of power outages for different consumer groups.

The analysis shows that all consumer groups can minimise costs incurred from power outages if they are given prior warning, and that costs vary from consumer group to consumer group and depend on the length and time of the outage.
The specific cost estimates are, however, subject to some uncertainty, e.g. because of a low response rate from enterprises and the complexity of the subject. Furthermore, questionnaire surveys generally have some degree of uncertainty as the type of questions asked can influence the result.
In this specific survey, both enterprises and households may have had difficulties estimating the cost of power outages, as power outages are rare in Denmark. Finally, it must be assumed that enterprises with high costs related to power outages will have been more inclined to take part in the survey. All in all, this means that the results of the analysis should be interpreted with caution.

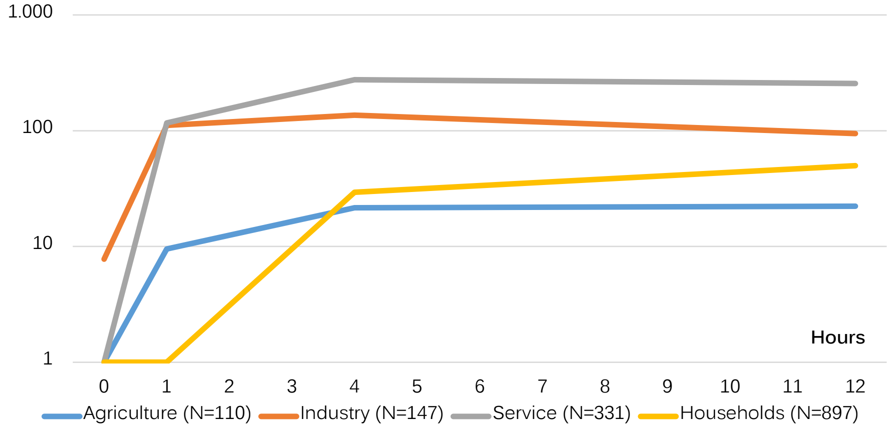
The DAMVAD analysis examines consumer outage costs but outages will not necessarily only lead to costs for consumers. An analysis performed by COWI of the costs of the power outage in 2003 revealed considerable outage costs for the electricity sector. A separate analysis of electricity-sector outage costs would therefore be relevant in relation to calculating the total socio-economic costs of outages.

MAIN CONCLUSIONS FROM THE DAMVAD ANALYSIS

Outage costs for different consumer groups:

- The analysis indicates that industrial

Figure 6: Normalised costs (DKK/kWh) as a function of duration, median.



Source: DAMVAD 2015
Note: The cost functions for the reference scenario are represented as a linear interpolation between four outage durations: 1 minute, 1 hour, 4 hours and 12 hours. Logarithmic scale. Fifty percent of households report costs of DKK 0 for outages of 1 minute's duration and 1 hour's duration, respectively.

and service enterprises have significantly higher outage costs than agriculture and households.

- The outage costs per lost kWh increase for all consumer groups in line with the duration of the outage up to the first four hours. After this, the costs per kWh drop or remain at a constant level, see figure 6.

- Therefore, it can be concluded that if the electricity system needs to pay/compensate consumers for curtailments, in situations with a one-minute curtailment, the cost per kWh will be least if agriculture, service enterprises and households are curtailed. For curtailments of one hour's duration or longer, the cost will be least if households and agriculture are curtailed.

- At least 50% of households report direct monetary costs of DKK 0 for outages of 1 minute's duration and 1 hour's duration, respectively. However, there are also respondents who also report monetary outage costs for shorter outage durations, which pulls the average for all households up to DKK 9 for 1 minute and DKK 106 for 1 hour.

The significance of prior warning

- Prior warning contributes to reducing outage costs significantly for all consumer groups. If warning is given a mere two hours before an outage, agriculture, service enterprises and households can reduce their outage costs by almost one-third on average. The results indicate that industrial enterprises require somewhat earlier notice to obtain similar reductions of their costs.

- Overall, the survey suggests that all consumer groups require between 8 and 24 hours' warning in order to reduce their outage costs as much as possible.

The significance of time of year, weekday and time of day

- Time of year has great significance for agriculture and households, in particular, while the costs for service and industrial enterprises are not subject to such seasonal variation.

- When looking at the significance of whether outages are on a workday or holiday/during the weekend, results indicate some significance for businesses, while the change in costs is insignificant for households.

- The time of day of the outage matters significantly for all consumer groups. Industrial and service enterprises have the highest costs per kWh lost during normal working hours (8 am to 4 pm). While agriculture and households clearly have the highest costs during the evening/night.

The significance of power failure backup measures

- A large number of enterprises in the survey have power failure backup measures in place. Sixty-nine percent of agricultural enterprises have some form of power failure backup measure in place. For service and industrial enterprises, the percentage is 51 and 46, respectively.

- Enterprises which have invested in power failure backup measures generally do not have lower costs per kWh than enterprises which have not invested in such measures. In the service sector, enterprises actually have considerably higher costs per kWh. This may seem counter-intuitive, but it could be because power failure backup measures only partly reduce the costs of enterprises, and because there are also costs associated with operating backup power units. At the same time, it would seem plausible that enterprises that have invested in power failure backup measures had higher costs of outages prior to their investment than other similar enterprises.

Source: DAMVAD

5 Recommendations

The stakeholders that took part in the project agree on a number of recommendations on the development of capacity adequacy forecasts and reporting. The objective of these recommendations is threefold. They are to:

1. promote a common understanding of how capacity adequacy contributes to security of electricity supply, and the methodology for determining capacity adequacy in future forecasts;

2. form a more precise framework for monitoring and reporting of security of electricity supply by Energinet.dk;

3. form the basis for follow-up work

The recommendations on the calculation methodology for capacity adequacy forecasts and follow-up work are aimed at stakeholders, the Danish Energy Agency and Energinet.dk. They have been prepared on the basis of the work to update capacity adequacy status in Denmark.

The recommendations on reporting on security of electricity supply are directed at Energinet.dk and its reports on security of electricity supply.

RECOMMENDATIONS ON THE METHODOLOGY APPLIED IN CAPACITY ADEQUACY FORECASTS

There are five overarching recommendations for preparing forecasts on capacity adequacy in future.

1. **A probabilistic methodology for capacity adequacy forecasts**

Although capacity balances are still being used internationally, there is increasing recognition that this methodology does not provide a complete picture of the overall security of electricity supply . There is a trend toward more countries using probabilistic calculations to assess capacity adequacy in the electricity system.

A probabilistic approach, which includes several variables (power plants, wind, solar energy, interconnectors and the transmission grid), provides a more accurate picture of the probability that enough capacity will be available to meet demand during all hours of the year.

Furthermore, a probabilistic approach to estimating future security of electricity supply is more compatible with the definition: the probability that electricity is available when demanded by consumers.

The project participants therefore recommend using a probabilistic methodology in security of supply forecasts.

2. **Capacity adequacy is reported as the frequency of expected capacity shortfalls and expected unserved energy**

A probabilistic approach to capacity adequacy initially measures the risk of capacity shortages in a given period. There are different concepts to describe the results of probability calculations on capacity adequacy.

In order to ensure good comparability of the results of capacity adequacy forecasts with reported historical capacity adequacy, it is recommended that capacity adequacy forecasts be calculated as the probability of a capacity shortage in a given hour, Loss Of Load Probability (LOLP), and the total energy demand expected not to be satisfied, Expected Unserved Energy (EUE).

LOLP describes the probability that a capacity shortage will occur during a given hour and is calculated using Monte Carlo simulations. It is converted to number of minutes per year by multiplying the probability that a capacity shortage occurs by 8,760 hours * 60 minutes.

EUE calculates the expected unserved energy demand during hours with a capacity shortage. Average demand per minute in Denmark is at around 65MWh. EUE is therefore expressed by calculating the capacity shortage in the model runs and dividing by 65MWh/minute. This expresses how much energy is unserved due to a lack of capacity adequacy.

When calculating EUE, possible impacts of a capacity shortage are included by estimating the probability that the capacity shortage identified in the model calculations leads to system collapse as a consequence of cascading failures caused by the fact that too few central power plant units are running. EUE therefore covers system security elements.

The methodology applied in calculations of EUE has been developed by Energinet.dk. Work to improve Energinet.dk's EUE methodology should be continued, so as to ensure the robustness of the methodology.

3. When preparing capacity adequacy forecasts, assumptions should be supplemented with a number of sensitivity analyses reflecting the most important uncertainties with regard to securing capacity adequacy in the future

It is important that the basis for capacity adequacy forecasts represents an outlook for the future which is plausible to stakeholders in the electricity sector. The assumptions applied in the analyses are decisive for the results arrived at. Therefore, a considerable aspect of work under this project was to understand and reach common ground with regard to the assumptions to be applied in forecasts.
As far as possible, assumptions, methodology and input data should be transparent and comparable to data used in other European countries and by collaborative fora such as Nord Pool and ENTSO-E. The project participants therefore recommend:

- that, as far as possible, publicly available data be used;
- that data be used which is based on a transparent and well-documented methodology

The project participants recommend that assumptions be supplemented by a number of sensitivity analyses. Sensitivity analyses cover changes in individual parameters in order to describe how uncertainties in assumptions affect capacity adequacy forecasts. As a general rule, sensitivity analyses should be carried out for both upward and downward adjustments of the individual assumption.
The sensitivities in forecasts should reflect relevant topics within future security of electricity supply. The project participants recommend that sensitivity analyses be performed for the following general topics:

- Production capacity in Denmark
- Interconnectors
- Flexible demand response
- Production capacity abroad.

4. As far as possible, capacity adequacy forecasts should be prepared in compliance with the requirements for capacity adequacy reporting by which Denmark is obligated internationally

International organisations such as ENTSO-E and the Energy Union are considering preparing a common methodology for estimating capacity adequacy. Where appropriate, future capacity adequacy forecasts should be prepared so that they comply with international methodologies. This will provide better possibilities to compare levels of security of supply in Denmark with the rest of Europe.

5. Flexible pricing programmes should be included in capacity adequacy forecasts where possible

When the definition of security of electricity supply was updated in 2014, the clause "when demanded by consumers" was added to the original definition. This opens up for the option to incorporate flexible pricing programmes in calculations of capacity adequacy. The deployment of smart meters by 2020 will provide better conditions for analysing the potential for incorporating demand-response programmes in capacity adequacy forecasts.

The project participants recommend that flexible pricing be included in capacity adequacy forecasts and compared to alternative models for achieving the desired level of security of supply, when there is sufficient knowledge and data about the potential for flexible pricing.

RECOMMENDATIONS CONCERNING SECURITY OF SUPPLY STATUS REPORTING

The Danish Electricity Regulation Committee recommended that Energinet.dk prepare an annual report for the Danish Minister for Energy, Utilities and Climate describing the status for security of electricity supply.

Participants in the project agree on the following recommendations for reporting security of electricity supply.

6. Outage statistics should be broken down by cause, should reflect a period of more than ten years, and should show the number of minutes for outages caused by lack of capacity

So far, outage statistics reporting has included information about whether outages are due to 'faults in own distribution area' or 'faults outside own distribution area'.
In future, outage statistics should include outages caused by capacity shortages, and situations like these should be described in order to arrive at a better understanding of why the situation arose. This provides greater transparency about changes in capacity adequacy over time and contributes to fine-tuning the methodology and the model. Outage statistics should therefore be reproduced for a longer period (more than ten years) in order to include rare, but extreme events in the electricity system, such as disruptions due to system security etc., which have high statistical significance.

7. Energinet.dk should include relevant Danish security of electricity supply indicators in reporting

Under Regulation (EC) No 714/2009 on conditions for access to the network for cross-border exchanges in electricity, Energinet.dk is already obligated to report incidents in the electricity system. The objective of the reporting method for incidents is to improve cooperation on operation of the electricity system. These reports primarily cover incidents associated with system security, and they ensure common classification of incidents. Reporting incidents helps draw attention to any inappropriate developments in the electricity system, but it is also an opportunity to foster dialogue about the underlying causes of incidents and about possible responses. Incidents are reported to ENTSO-E.

As a supplement to the above, it is recommended that reporting on security of electricity supply by Energinet.dk include a number of indicators and explanations for their significance for security of supply. These indicators focus mainly on market interventions by the system operator. The indicators concern both the security and adequacy of the electricity system.

Relevant indicators could be:

- strategic reserves used;
- limited availability of interconnector capacity;
- voluntary and forced curtailment of consumers;
- rejected plans for revision;
- forced operation;
- heightened alert' operation and emergency operation;
- lack of market function;
- use of 2nd auctions, when these are implemented;
- announced urgent market messages on high prices.

RECOMMENDATIONS CONCERNING NEXT STEPS

8. A technical forum should be established to continue discussions on how to develop the methodology for calculating capacity adequacy and security of electricity supply in general

The methodology used in capacity adequacy forecasts should be continuously improved as assumptions and political priorities change over time. There is a desire to continue the collaboration among stakeholders in a less formal structure than applied for this project. Such continued collaboration should focus e.g. on the technical aspects of developing capacity adequacy forecasts. Furthermore, the impact on system security of the development toward fewer large-scale and small-scale power plants should be analysed in more detail, including the expected future market participation of these plants.

The project participants recommend that a technical forum be established, initially comprising the working group participants, to continue discussions on how to develop methodologies to calculate capacity adequacy and security of electricity supply in general

9. Recommendations pertaining to work on revising the EU directive on security of electricity supply

In connection with the upcoming revision of the security of electricity supply directive, the European Commission will prepare a European methodology for assessing capacity adequacy in Member States. Recommendations from the project could serve as input for Denmark's negotiating position.

10. The recommendations can be technical input for developing legislation for annual reporting on security of electricity supply

The Danish Electricity Regulation Committee recommended that Energinet.dk prepare an annual security of electricity supply report for the Danish Minister for Energy, Utilities and Climate, describing Danish security of electricity supply in an historical as well as a forward-looking perspective. If a legislative framework is to be prepared for such a report, it is proposed that the recommendations in this project form the basis for this.

Annex B
Project participants

	CONTROL GROUP	WORKING GROUP
The Danish Energy Agency (chairman)	Managing Director Morten Bæk	Lars Nielsen, Edward James-Smith, Sandra Friis-Jensen and Sigurd Lauge Pedersen
The Confederation of Danish Industry	Deputy Director Troels Ranis	Ingeborg Ørbech
The Danish Energy Association	Managing Director Lars Aagaard	Stine Leth Rasmussen and Christian Dahl Winther
The Danish District Heating Association	Director Kim Mortensen	Nina Detlefsen
The Danish Wind Turbine Owners' Association	Director Asbjørn Bjerre	Henrik Skotte
Energinet.dk	Director Søren Dupont Kristensen	Carsten Vittrup and Stine Grenaa Jensen
The Danish Consumer Council	Deputy Director Vagn Jelsøe	Søren Dyck-Madsen
The Danish Wind Industry Association (DWIA)	Managing Director Jan Hylleberg	Martin Risum Bøndergaard
The Danish Agriculture & Food Council	Head of Department Jens Astrup Madsen	Mikkel Stein Knudsen

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Danish Energy Agency
Amaliegade 44
1256 Copenhagen K
Tel.: +45 33 92 67 00
Fax: +45 33 11 47 43
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www.ens.dk

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