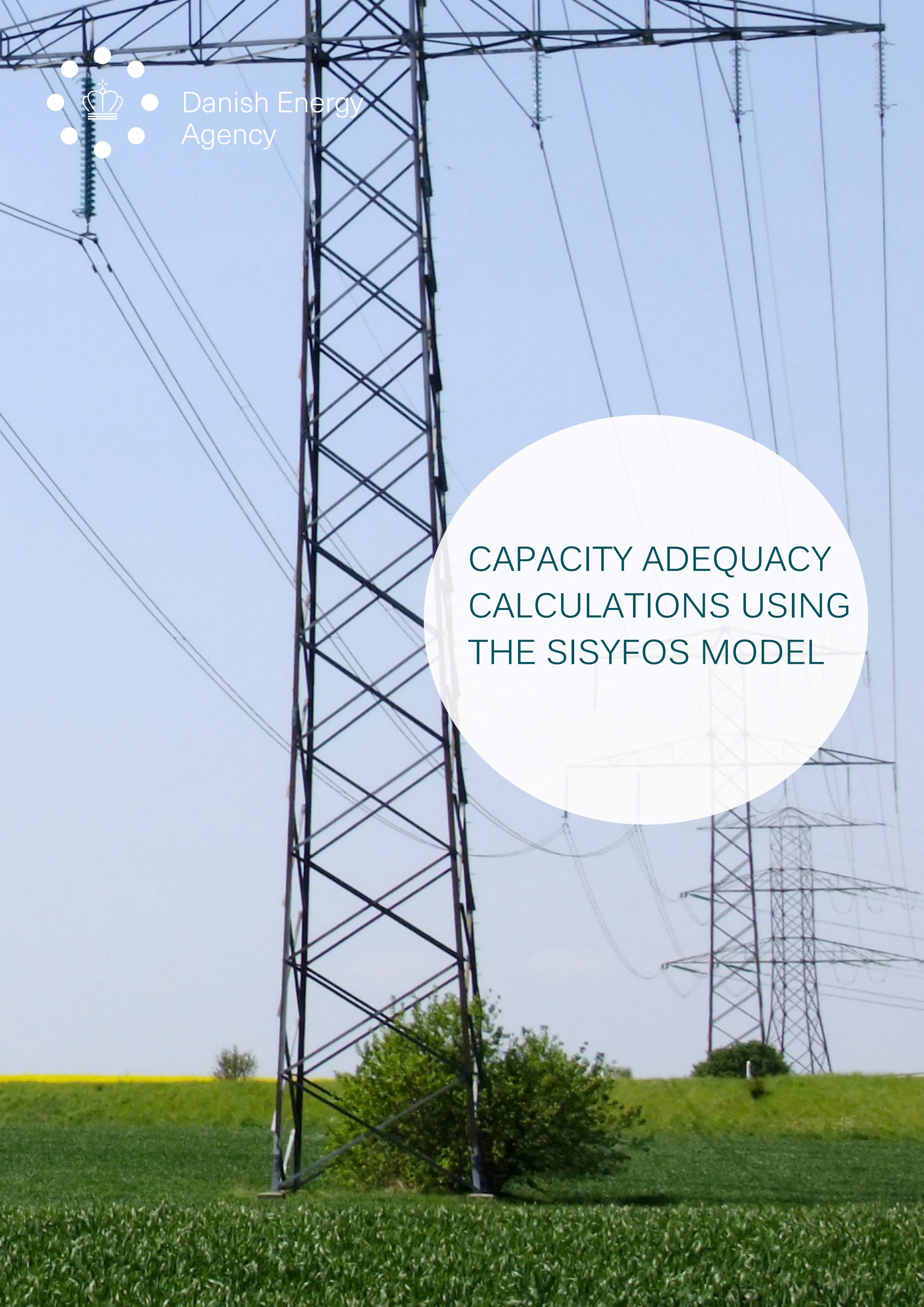

Danish Energy
Agency

CAPACITY ADEQUACY CALCULATIONS USING THE SISYFOS MODEL

Contents

Summary

This is a background report to the *Security of electricity supply in Denmark* report. This background report presents calculations which forecast Danish capacity adequacy in the period 2015 to 2025, using the Danish Energy Agency's SISYFOS model. 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). The calculations are based on a similar analysis from 2014, but using a more detailed data set and modelling capacity in neighboring countries[1].

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. 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 also represented as point suppliers.

Estimation has been performed on the basis of a set of baseline data as well as a number of sensitivities. 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[2]. For Danish wind power, photovoltaic power and electricity demand, the 2014 baseline projection by 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 stochastic model, SISYFOS, was used for the calculations. SISYFOS calculates the probability of capacity shortages arising in a given hour (Loss of Load Probability, 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 forecasts 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 conclusions from calculations:

- Danish 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. The Danish electricity system's dependence on other 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 is expected to have more capacity through interconnectors in 2020 than peak demand in the Danish power system, which strengthens capacity adequacy considerably.

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[1] Analysis of Danish power system function. Danish Energy Agency, 2014.

[2] Results from a questionnaire of small-scale CHP plants. Grøn Energi (Green Energy) 2013.

- The national calculation includes situations with capacity shortages in DK2 throughout the period. 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 non-negligible compared with the total number of minutes' outage caused by the low-voltage and transmission grid (around 50 minutes/year). There will not be capacity shortages in DK1 until around 2025 and these will be only minor shortages. Capacity shortage has been estimated in minutes in two different ways. LOLP minutes refer to the expected probability 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 electricity 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 on interconnectors than purely physical ones. However, 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 peak 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.

(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

Table 1 **Calculated capacity shortages (national)** Blue figures: LOLP converted to number of minutes' capacity shortage per year. Red figures: Expected unserved energy (EUE) converted to weighted minutes/year.

A number of sensitivity analyses have been performed. The results of these can be summarised as follows:

- 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 shortages 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 probability of failure on interconnectors and an increased probability of neighbouring countries not being able to supply electricity to Denmark will dramatically reduce Danish capacity adequacy.
- Closures 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 calculation 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 that, were it not there, generation adequacy would be poorer. Furthermore, if more wind power is developed, generation adequacy will improve.
- If around 200MW (perfectly) flexible demand were available in DK1 and DK2, it could remove around half of calculated capacity shortages in 2025.

Introduction

This report describes regional and national calculations of Danish capacity adequacy for 2015, 2020 and 2025 using the Danish Energy Agency's Monte Carlo simulation model; SISYFOS.

Capacity adequacy is an element of electricity supply, i.e. *the probability that electricity is available when demanded by consumers*. So far, Denmark has not experienced power outages as a consequence of lack of capacity adequacy. Whereas capacity adequacy calculations predict insignificant capacity problems today, there could be significant problems in the future. For several years, Danish security of electricity supply has been at around 99.99%, which means an average outage time of around 50 minutes per year for the ordinary consumer. In a historical perspective, lack of capacity adequacy has never contributed outage minutes. The objective of the calculations in this report is to provide a basis for assessing whether or not lack of capacity adequacy will continue to contribute only insignificantly to power outages in the future (however, without considering what constitutes 'insignificant').

These calculations of capacity adequacy do not include the internal electricity grids (the distribution and transmission grids) and only include electricity generation plants and electricity connections from one electricity area to another (interconnectors, the Great Belt connection and connections between areas with significant bottlenecks). There may be situations in which decommissioning of a CHP plant will affect the security of electricity supply in a local area. Local affects of this type are not covered in the calculations.

Furthermore, the calculations do not directly address security of heat supply, although decommissioning of CHP capacity could also affect the supply of heat. Usually, there will be considerable reserve capacity in heat boilers. It is therefore fair to assume that the physical security of heat supply will not be affected considerably by former or future decommissionings of CHP plants (although the *price* of heating could be affected considerably).

The SISYFOS model

SISYFOS is a Monte Carlo simulation model which, based on rolls-of-the-dice, simulates different outcomes for power plants and/or power lines in a large interconnected electricity system. Using hourly series for electricity demand, wind power, photovoltaic power, etc., the model looks for (rare) combinations of events which can lead to capacity shortages. Loss-of-probability (LOLP) is calculated and converted into number of minutes' capacity shortage per year. Furthermore, expected unserved energy (EUE) is calculated using a methodology developed by Energinet.dk, along with the associated average number of outage minutes (which, in principle, can be compared with historical outage minutes).

SISYFOS uses various data about generation plants and power lines (geographical location, capacity, probability of failure, frequency of planned outage, year of commissioning/decommissioning, and data on how available capacity of combined heat and power plants depends on ambient temperature . Furthermore, data on annual electricity demand, wind power generation and photovoltaic power generation is used, as well as hourly series to distribute this data.

For a more detailed description of the SISYFOS model, see Annex A.

Calculations of LOLP are associated with considerable uncertainties. Partly because some of the data used is uncertain, and partly because the results are statistically uncertain due to the roll-of-the-dice methodology applied. For this and other reasons, a number of sensitivity calculations were carried out. By running a sufficiently large number of calculations, statistical uncertainty can be reduced.

Applied data

For practical reasons, a set of baseline data has been used and this has been supplemented by a number of sensitivity analyses. The assumptions applied are described below. As far as possible, publicly available data has been used. However, there are a few exceptions in the event of where confidential data has been used instead.

Geographical breakdown

Three data sets with different geographical breakdown have been used.

One of the data sets (Data2) covers only Denmark (broken down into two electricity areas: western Denmark = DK1 and eastern Denmark = DK2). Another data set (Data16) covers Denmark (two areas), Norway (five areas), Sweden (four areas), Finland (one area), Germany (two areas), the Netherlands (one area) and United Kingdom (one area). See figures 1 and 2. The last data set (Data9) is a simplified version of Data16 covering only 9 electricity areas: Denmark (two areas), Norway (one area), Sweden (three areas), Finland (one area), Germany (one area) and the Netherlands (one area). Data9 was developed for the following reasons:

1. The calculation time in SISYFOS increases with the number of nodes.
2. Internal bottlenecks in Norway and Northern Sweden are deemed to be less significant in terms of Danish capacity adequacy. For example, Data16 includes bottlenecks in connection with supply to the Trondheim area (Norway3).
3. Bottlenecks in Northern Germany are also deemed to be less significant in terms of Danish capacity adequacy. Although these bottlenecks *are* significant for the possibility of transmitting Danish electricity southward, the capacity adequacy in Denmark relies more heavily on the possibility of transmitting electricity from Germany northward to Denmark.
4. Data16 includes the United Kingdom, because a connection from DK1 to the United Kingdom is considered potentially feasible. However, since the analyses suggest relatively good capacity adequacy for DK1, an electricity connection to the United Kingdom can hardly be justified merely on the grounds of ensuring capacity adequacy. See also under sensitivity calculations.

Interconnectors to countries not covered in the data set are represented by a number of interconnectors to countries for which there is a probability of 'failure' (while, at the same time, the interconnectors themselves can become subject to failure). This means that countries not covered in the data set are described as 'power plants' with a certain probability of failure (and this probability depends on the country's capacity situation).

Source: Nord Pod Spot

Figure 1 Breakdown by electricity areas in the Nordic countries.

Figure 2 ENTSO-E members. Source: www.entsoe.eu.

Generation capacity

- Denmark: For Danish power plants and CHP plants, data for 2015 is from the 2013 annual energy-production statistics from the Danish Energy Agency. For the period 2020 to 2025, Energinet.dk's analysis assumptions 2015 to 2035 have been used. However, there are a few exceptions. For gas-fired, decentralised plants, a survey of decentralised plants performed by the Danish District Heating Association in November 2013 has been used. For wind and solar plants, the assumptions in the Danish Energy Agency's baseline projection from 2014 have been used.
- Norway: Energinet.dk's data broken down into five areas (NO1 (Oslo and surroundings), NO2 (Southern Norway), NO3 (Trondheim and surroundings), NO4 (Northern Norway) and NO5 (Bergen etc.)).
- Sweden: Energinet.dk's data broken down into four areas (SE1 (Northern Sweden), SE2 (Mid Sweden with Sundsvall etc.), SE3 (Goteborg, Stockholm etc.) and SE4 (Southern Sweden).
- Finland: Scenario Outlook and Adequacy Forecast 2014 from ENTSO-E (scenario B ('best estimate'). In the following referred to as SO&AF-B. This is a publication from ENTSO-E, which estimates expected capacity adequacy for the period up to 2025 on the basis of a standard methodology and input from system operators in the individual countries. Capacity adequacy is estimated on the basis of capacity by type as a percentage of the electricity demand in high-load periods determined on the basis of a 'best estimate' and a 'conservative estimate'. For 2030, a number of scenarios have been used. The methodology applied can best be described as 'advanced capacity balances', and it is therefore not a probabilistic analysis.
- Germany: Energinet.dk data broken down into two areas: Schleswig-Holstein (SWHO) and rest-of-Germany (RDE).
- The Netherlands: SO&AF-B, see above.
- The United Kingdom: SO&AF-B, see above.

Figures 3 - 9 illustrate the capacity balance 2020 for the seven countries included explicitly in SISYFOS.

The capacities assumed in SISYFOS are compared with four other forecasts:

1. Pentalateral Energy Forum: Generation Adequacy Assessment. 5 March 2015. AT, BE, CH, DE, FR, LU, NL, (IT, ES, GB).
2. SO&AF-B.
3. ENTSO-E: Scenario Outlook And Adequacy Forecast 2014-2030 scenario A ('conservative'). In the following referred to as SO&AF-A.
4. The Danish Energy Association has published a theoretical capacity forecast which, based initially on existing power plants (from the Platts database), and using fixed lifespans for different power plant technologies[3], calculates future capacity with no new investments in thermal capacity. This analysis does not represent the Danish Energy Association's expectations; it is used solely to illustrate the extreme situation where there is no new development or renovation of thermal capacity, and instead only wind and solar capacity are expanded.

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[3] Steam turbine plants: 45 years; gas turbines (OCGT and CCGT): 30 years; engine plants: 25 years. Furthermore, it is assumed that a number of specific plants will be shut down e.g. in GB as a consequence of the Industrial Emissions Directive.

The figures show two forecasts of electricity demand: 1) 'Load Jan 19:00' describes demand at 7 pm in January, in the same way as ENTSO-E; and 2) 'MaxLoad' describes the annual hourly peak demand using 2013 hourly curves and the assumed annual consumption figures.

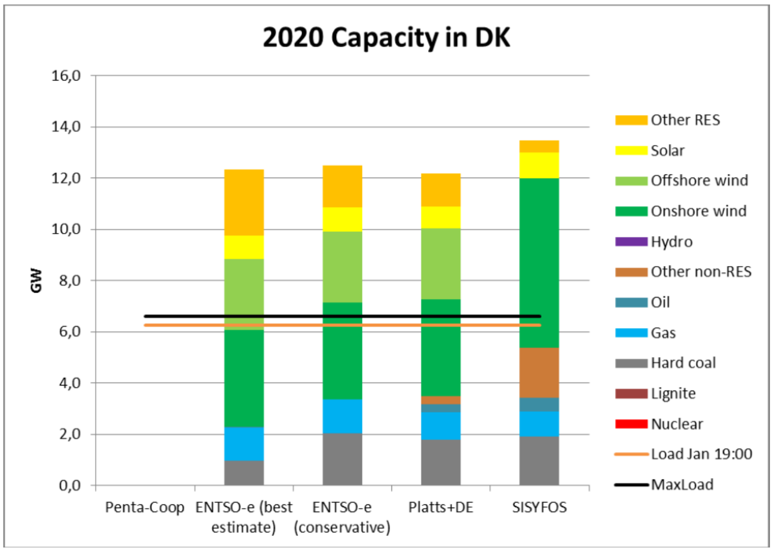

Figure 3 Different forecasts of capacity balance for Denmark in 2020.

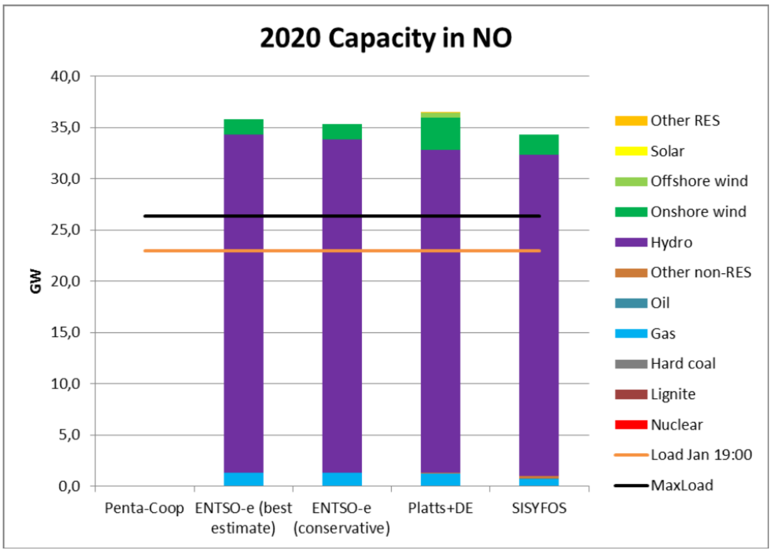

Figure 4 Different forecasts of capacity balance for Norway in 2020.

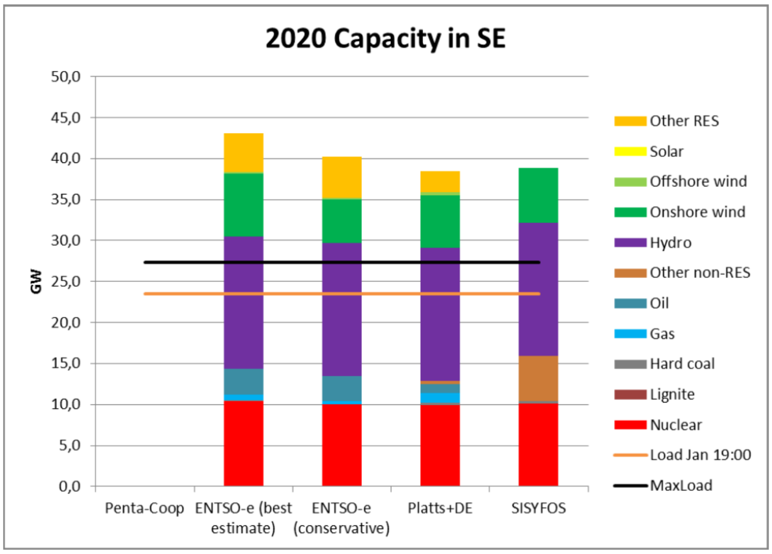

Figure 5 Different forecasts of capacity balance for Sweden in 2020.

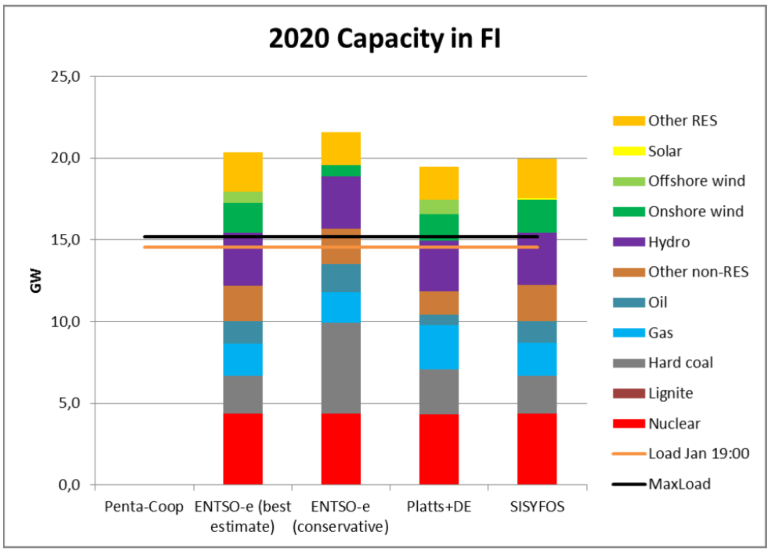

Figure 6 Different forecasts of capacity balance for Finland in 2020.

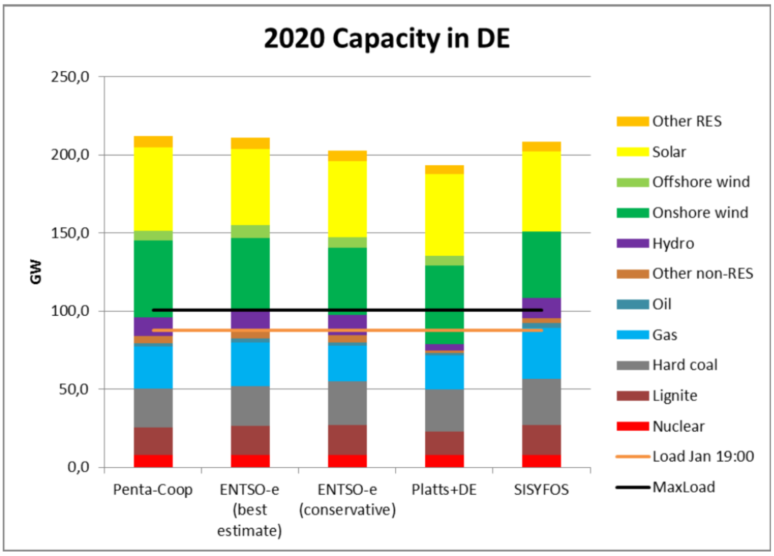

Figure 7 Different forecasts of capacity balance for Germany in 2020.

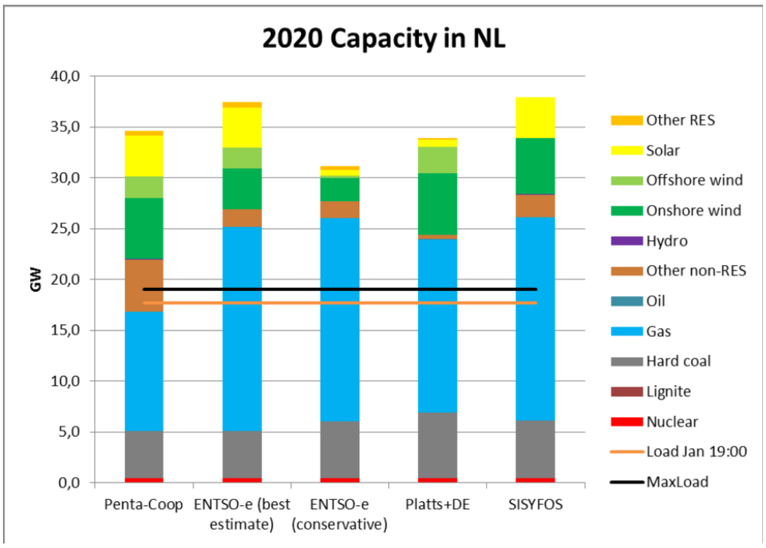

Figure 8 Different forecasts of capacity balance for the Netherlands in 2020.

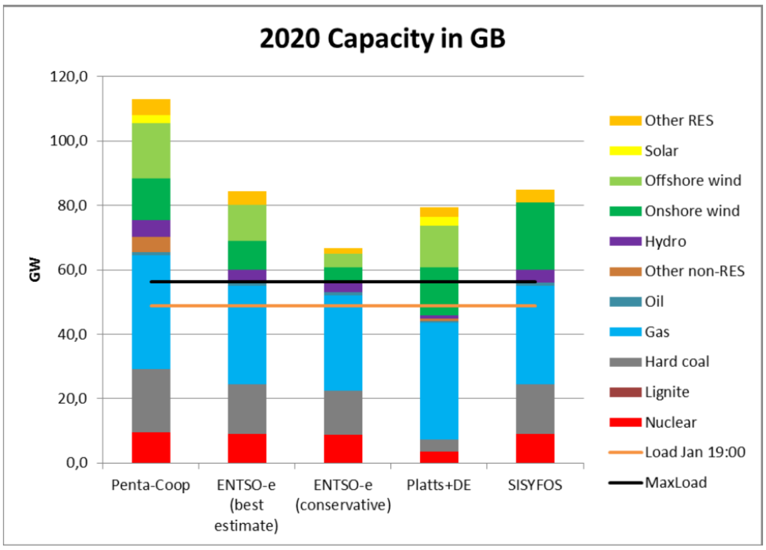

Figure 9 Different forecasts of capacity balance for the United Kingdom in 2020.

It should be noted that, in general, different categorisations have been used in the various forecasts, which makes comparison difficult. For example, SISYFOS does not break down wind power into onshore and offshore wind power (i.e. all wind power in the graph is called onshore wind power). Furthermore, SISYFOS calculates wind capacity 'backwards', starting with the annual energy value and then calculating the capacity from the peak value of the hourly curve. Finally, in some instances the forecasts use different categorisations of thermal capacity.

In general, all the different calculations forecasting future capacity and peak demand are rather uncertain, even in a relative short term. For example, this is illustrated by a sensitivity calculation using another (considerably lower) capacity expansion in Denmark's neighbouring countries than assumed by ENTSO-E.

Power lines

Table 2 below shows the assumptions for power lines internally in the model (external power lines are considered as 'power plants', see below).

Line	From	To	Cap. from	Cap. to	Number	Type	Outage
Great Belt	DK1	DK2	590	600	1	HVDC	8.0%
Skagerrak	DK1	NO2	1532	1532	4	HVDCi	8.0%
Kontiskan	DK1	SE3	740	680	2	HVDCi	8.0%
Germany connection	DK1	SWHO	1780	1500	5	ACi	5.0%
Kontek	DK2	RDE	600	600	1	HVDCi	8.0%
Soderåsen	DK2	SE4	1000	1000	2	ACi	5.0%
Morarp	DK2	SE4	700	300	2	ACi	5.0%
Borrby (Bornholm-Sweden)	DK2	SE4	60	60	2	ACi	5.0%
NO4_SE1	NO4	SE1	700	600	1	ACi	5.0%
NO4_SE2	NO4	SE2	250	300	1	ACi	5.0%
NO3_SE2	NO3	SE2	600	1000	1	ACi	5.0%
NO1_SE3	NO1	SE3	2145	2095	2	ACi	5.0%
Ivalo-Varangerbotn	NO4	FIN	100	100	1	ACi	5.0%
SE1_FI	SE1	FIN	1500	1100	3	ACi	5.0%
SE3_FI	SE3	FIN	1200	1200	2	HVDCi	8.0%
V.Kårrstorp-Herrenwyk	SE4	SWHO	600	600	1	ACi	5.0%
SWHO-RDE	SWHO	RDE	6870	6870	6	AC	5.0%
NO_GB	NO2	GB	0	0	1	HVDCi	8.0%
BritNed	NL	GB	1000	1000	1	HVDCi	8.0%
NorNed	NO2	NL	700	700	1	HVDCi	8.0%
NL_RDE	NL	RDE	3500	3500	2	AC	5.0%
DK_GB	DK1	GB	0	0	1	HVDCi	8.0%
Cobra	NL	DK1	700	700	1	HVDCi	8.0%

Table 2 Existing power links (interconnectors).

The sources of these capacities are: Energinet.dk, ENTOSO-E and a consultancy survey prepared by the German consultancy firm B.E.T. for the Danish power system function analysis.

In addition to existing power lines, it is assumed that the following lines will be established in the period up to 2030:

- Capacity enhancement between Jutland and Germany before 2020 (1000 MW).
- New connection between Zealand and Germany via Kriegers Flak 2019 (400 MW)
- Nordlink (Norway-Germany) 2019 (1400 MW)
- Internal capacity enhancement between Schleswig-Holstein and the rest of Germany before 2020 (8000 MW) and before 2025 (another 6000 MW).
- Cobra 700 MW between the Netherlands and DK1 2019.
- A connection to the United Kingdom (1400 MW; pending decision and not included in the baseline estimation).

Assumptions on unplanned and planned outage and co-generation of heat

A number of factors are used to determine the probability that plants and power lines will be available within the individual time steps. Two parameters are used to describe the co-generation-of-heat factor: DH_constant is the share of the capacity which is not temperature sensitive and, therefore, available year round (except during failures and audit shutdowns). DH_variable is the temperature-sensitive share of the capacity, which means less availability in the summer. See table 3.

Type	Description	Unplanned Outage	Planned Outage	DH_constant	DH variable
CHP	Dec. CHP (unspecified)	8.0%	9.6%	0.3	0.7
CHPwaste	Dec. CHP (waste)	8.0%	9.6%	1	0
CHPg	Dec. CHP (gas)	8.0%	9.6%	0.3	0.7
ICHP	Industrial CHP	8.0%	9.6%	0.9	0.1
ICHPg	Industrial CHP (gas)	8.0%	9.6%	0.9	0.1
Nuclear	Nuclear power	8.0%	7.7%	1	0
HydroReg	Regulatable hydropower	8.0%	0.0%	1	0
Reserve	Reserve power	8.0%	1.9%	1	0
LCHPmbio	Large-scale CHP (biomass back pressure)	8.0%	7.7%	0.8	0.2
LCHPcoal	Large-scale CHP (coal, condensate or extraction)	8.0%	7.7%	1	0
LCHPlignite	Large-scale CHP (lignite, condensate or extraction)	8.0%	7.7%	1	0
LCHPgas	Large-scale CHP (gas, condensate or extraction)	8.0%	7.7%	1	0
LCHPoil	Large-scale CHP (oil, condensate or extraction)	8.0%	7.7%	1	0
CHPbio	Dec. CHP (biomass)	8.0%	9.6%	0.3	0.7
AC	AC power line	5.0%	0.0%	1	0
OtherRE	Unspec. Renewable energy installation	8.0%	9.6%	1	0
HVDC	HVDC line	8.0%	0.0%	1	0

Table 3 Failure rate and co-generation of heat for plants and power lines.

Wind power, photovoltaic power and run-off-river hydropower is modelled using annual energy and an hourly series. Therefore, failure rates etc. are not included for these technologies.

Assumptions concerning countries outside of the model

For Data16, as well as for Data9 and Data2, there are a number of connections between areas included in model and areas outside of the model. These are modelled using random failures of power lines connecting to the areas/countries and random 'failures' of areas/countries from where the lines originate; in the following referred to as 'country failures'; abbreviated as CF). For countries outside of the model, a single CF value is used.

In the regional calculation for DK, NO, SE, FI, DE, NL and GB, CF is used for the following countries: Russia, Poland, France, Estonia, Lithuania, the Czech Republic, Switzerland, Belgium, Austria, Ireland, Northern Ireland and Luxembourg.

For the national calculation, CF is used for the countries with which Denmark is connected, or to which Denmark will be connected in the future, i.e. Norway, Sweden, Germany, the Netherlands and (possibly) the United Kingdom.

The size of the CF value is determined on the basis of a calculation of available reserves in the countries as described in SO&AF-B. It is assumed there is a functional correlation between available reserves and the country failure rate as illustrated in figure 10.

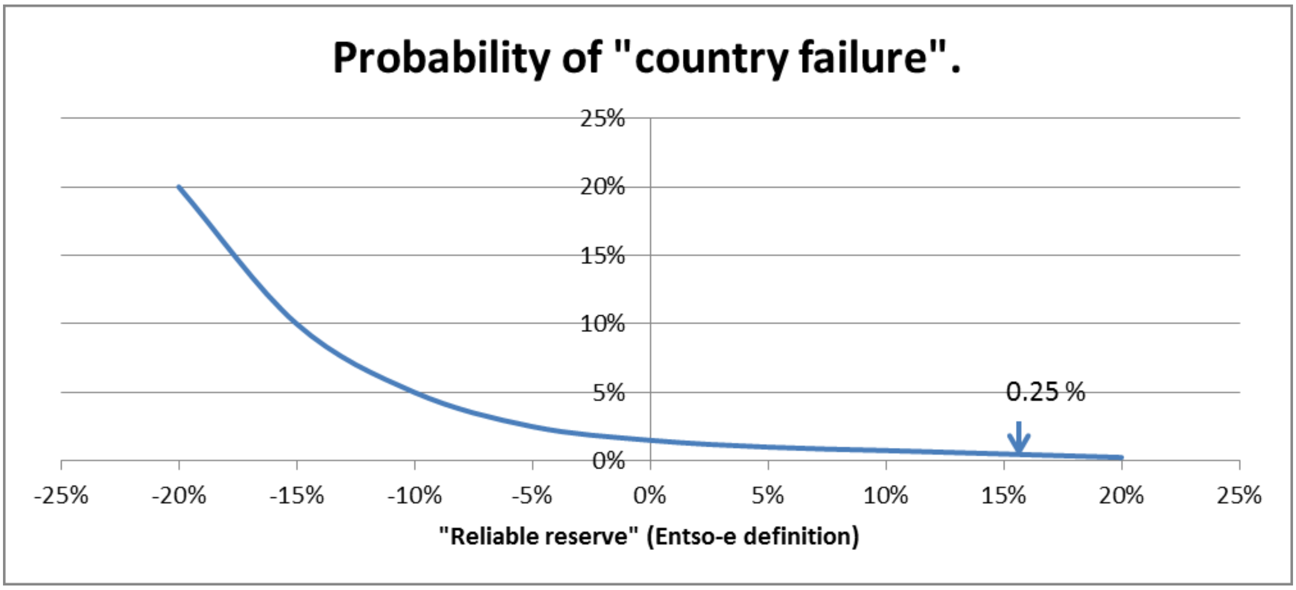

Figure 10 Assumed correlation between CF and reliable reserve from SO&AF-B

It could be expected that, all else being equal, an electricity area located east or west of Denmark would have greater value for the security of the Danish electricity supply than an electricity area located north or south of Denmark, because there is a less significant correlation between wind power, photovoltaic power and electricity demand. However, an effect of this has not been incorporated in the assumptions for country failure. The geographical spread, including the east-west / north-south issue, is included implicitly in the regional calculation, however not in the national calculation.

The above functional (and inherently uncertain) correlation means that CF changes over time. The resulting CF values are given in table 4.

Onshore	2015	2020	2025
Austria	0.25%	0.25%	0.25%
Belgium	1.50%	1.50%	1.00%
Switzerland	0.75%	1.00%	2.50%
Czech Republic	0.25%	0.25%	2.50%
Germany	1.00%	1.50%	5.00%
Estonia	0.75%	2.50%	10.00%
Finland	5.00%	1.50%	1.50%
France	0.75%	1.00%	1.50%
United Kingdom	0.50%	0.75%	0.50%
Ireland	0.25%	0.25%	0.75%
Lithuania	0.25%	1.50%	0.25%
Luxembourg	0.25%	0.25%	0.25%
The Netherlands	0.25%	0.25%	0.25%
Norway	0.25%	0.25%	0.25%
Poland	0.75%	1.00%	1.00%
Sweden	0.25%	0.50%	0.50%
SE3	0.75%	0.75%	0.75%
SE4	1.50%	1.50%	1.00%

Table 4 CF ('country failure rates' for various electricity areas)

Note the following regarding these figures:

- As a general rule, CF increases over time, as most of the countries will have a lower reliable reserve in the future.
- Energinet.dk uses a value of 1.5% for Germany. This corresponds with the SISYFOS value in 2020. SISYFOS uses a greater CF value for Germany in 2025 (5%).
- CF for Norway is 0.25% throughout the period. This corresponds with the value assumed by Energinet.dk.
- For Sweden, on average, CF is 0.25% today, increasing to 0.5% from 2020. However, since there is a connection to SE3 and SE4, and since there are bottlenecks in Sweden, a higher CF has been used for SE3 and SE4. Here, Energinet.dk's values have been used.
- For the Netherlands, SISYFOS uses a value of 0.25% for the entire period. This is not as high as the 1% used by Energinet.dk.
- For the United Kingdom, SISYFOS uses a value of 0.5-0.75%. This is not as high as the 2% used by Energinet.dk.

At all events, on the one hand CF is very difficult to estimate, but on the other hand it has great significance. For a more detailed discussion of this matter, see the sections below with results and sensitivity analyses.

Hourly values

Normalised hourly values in MW/TWh of electricity demand, wind power generation, photovoltaic power generation and run-off-river hydropower have been used. The hourly values are concurrent for 2013 and 2014, and stated as CET winter-time. The hourly values have been scaled up and down using the annual value in TWh of electricity demand, wind power generation, photovoltaic power generation or run-off-river hydropower. So far, it has not been possible to obtain suitable concurrent sets of hourly values from earlier years for all countries.

It is therefore assumed that the historical variations observed in 2013 and 2014 reflect the likely combinations of wind power, solar power and electricity demand for the future. The effects of storm Allan on 27-28 October 2013 and storm Bodil on 4-7 December are included in the time series used.

Hourly values are missing in some cases. In these cases hourly values for the same period but from another adjacent electricity area have been used. The risk of capacity shortage is therefore overestimated (as the geographical evening-out has been underestimated).

The hourly values for electricity demand are from Energinet.dk's market data (Denmark) and ENTSO-E (other countries than Denmark).

Hourly values for wind power are from Energinet.dk's market data (Denmark), the Danish Energy Association (GB 2014 and Sweden), www.pfbach.dk (Finland 2013, Germany, GB 2013).

Hourly values for photovoltaic power are from Energinet.dk's market data (Denmark 2014), the Danish Energy Association (Sweden) and www.pfbach.dk (Germany).

Hourly values for run-off-river hydropower are from www.nve-no (synthetic hourly series based on weekly values for inflow in Norway; used for all of the Nordic countries) and Energinet.dk (Germany).

The hourly values applied are described in more detailed in Annex B.

Capacity adequacy 2015-2025 (regional calculations using Data16)

A simulation was run for the years 2020 and 2025 using SISYFOS with the Data16 dataset (table 5). No simulation was run for 2015, as it has been assumed that this simulation will give lower LOLP values than 2020. Capacity shortages only occur in Norway 3 (the Trondheim area). The calculations show no capacity shortages in Denmark, or rather: the values are lower than the statistical uncertainty, i.e. there is a ~90% certainty that the true LOLP value is lower than 1.1 minutes/year. See Annex A for a description of the statistical uncertainty. No simulation was run for 2015, as it has been assumed that this simulation will give lower LOLP values than 2020.

Area	2015	2020	2025
dk1	-	<~1.1	<~1.1
dk2	-	<~1.1	<~1.1
no1	-	<~1.1	<~1.1
no2	-	<~1.1	<~1.1
no3	-	6.8	7.7
no4	-	<~1.1	<~1.1
NO5	-	<~1.1	<~1.1
SE1	-	<~1.1	<~1.1
SE2	-	<~1.1	<~1.1
SE3	-	<~1.1	<~1.1
SE4	-	<~1.1	<~1.1
FIN	-	<~1.1	<~1.1
SWHO	-	<~1.1	<~1.1
RDE	-	<~1.1	<~1.1
NL	-	<~1.1	<~1.1

Table 5 The probability of capacity shortages (LOLP minutes/year) using Data16. Hourly curves from 2013. Number of simulations: 1.16 million

Figure 11 shows the calculated import dependence for the various electricity areas included in the simulation. The figure shows that NO1 (Oslo and surroundings) and SE4 (Southern Sweden) have the highest import dependence. The figure also shows that Danish import dependence increases over time.

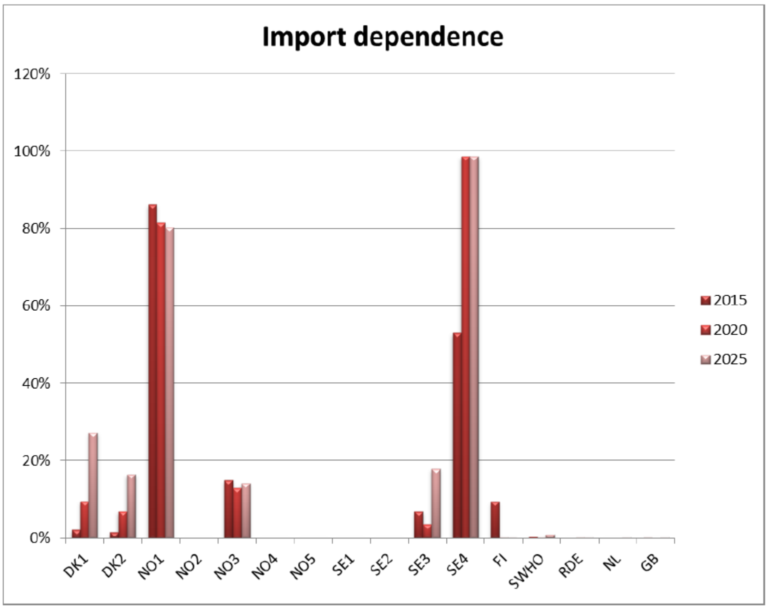

Figure 11 The import dependence of the 16 electricity areas.

Figure 12 shows the calculated average capacity reserve available for 2015, 2020 and 2025 as a percentage of the area's peak demand, i.e.

(Average available capacity - Peak demand)/Peak demand

As opposed to the installed capacity, the average capacity reserve takes account of the reliability of the plants. For example, wind capacity is now only included at around 33% of the installed capacity (Denmark) and 20% of the installed capacity (Germany). Photovoltaic power is included at around 15% of the installed capacity. Thermal plants are included at between 50% and 85% of their installed capacity, depending on the co-generation-of-heat factor. Interconnectors are not included.

Amongst other things, the figure shows that

- The average capacity reserve in DK1 and DK2 decreases over time.
- The average capacity reserve in DK1 is larger than in DK2.
- The average capacity reserve is positive in both Norway and Sweden, but there are large differences between the individual price areas. For example, the Oslo area and Southern Sweden have considerably lower average capacity reserves than the average for the all of the countries included.
- The average capacity reserve in Finland is negative today, but improves in step with the phase-in of more nuclear power.
- The average capacity reserve in Germany is positive and fairly constant.

- The average capacity reserve in the Netherlands is positive but decreasing.
- The average capacity reserve in the United Kingdom is positive and increasing.

The average capacity reserve is **not** a direct measure of capacity adequacy or security of electricity supply, however it is an indication of the degree to which Denmark can rely on supply from the individual areas.

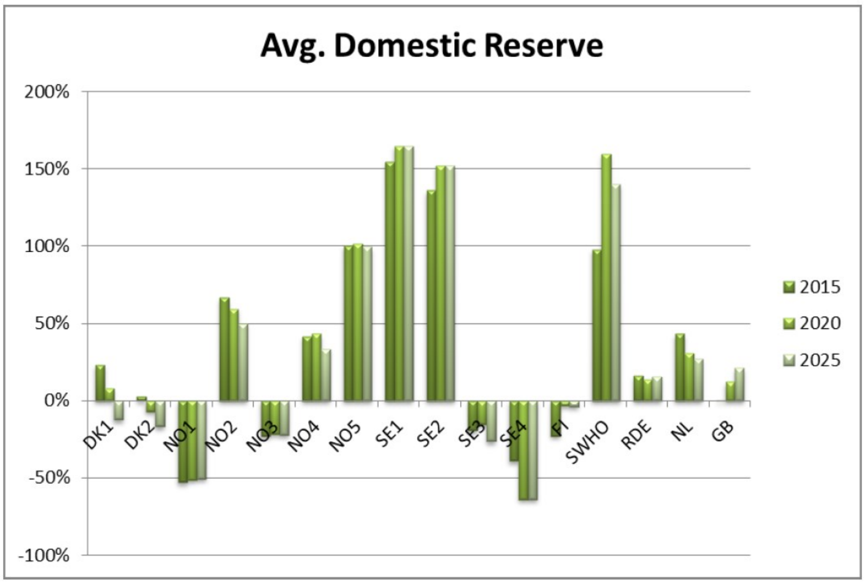

Figure 12 Average capacity reserve without interconnectors.

Figure 13 below shows the installed capacity through interconnectors from the individual electricity areas in Data16 for the year 2020, as a percentage of the annual peak demand. Annual peak demand for DK1 has around 140% cover through interconnectors.

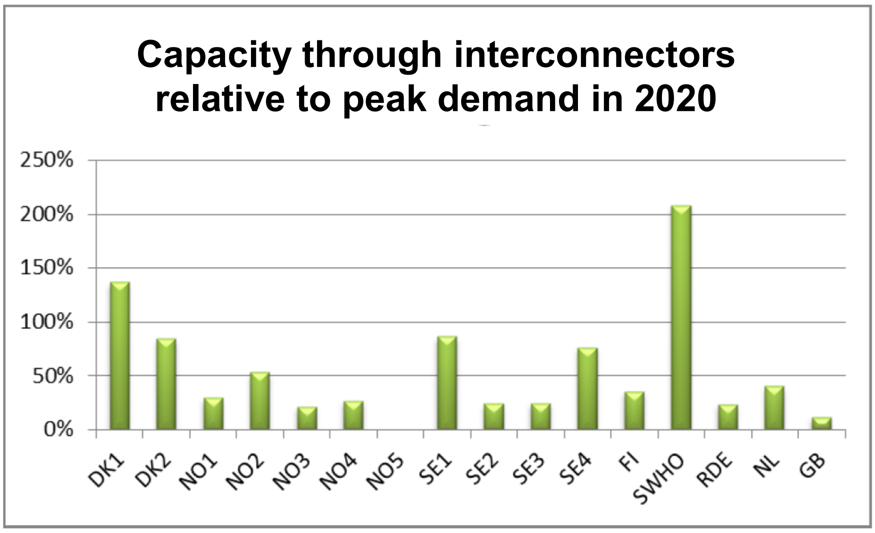

Figure 13 Installed capacity in interconnectors 2020 as a percentage of peak demand for the electricity areas considered.

Capacity adequacy 2015 to 2025 (regional calculations using Data9)

A simulation was also run with the Data9 dataset for the years 2020 and 2025 (table 6). No simulation was run for 2015, as this simulation has been assumed to give lower LOLP values than 2020.

Area	2015	2020	2025
DK1	-	<~0.7	<~0.7
DK2	-	<~0.7	0.6
NO	-	<~0.7	<~0.7
SE12	-	<~0.7	<~0.7
SE3	-	<~0.7	<~0.7
SE4	-	<~0.7	<~0.7
FIN	-	<~0.7	<~0.7
DE	-	<~0.7	<~0.7
NL	-	<~0.7	<~0.7

Table 6 The probability of capacity shortages (LOLP minutes/year) using Data9. Hourly curves for 2013 and 2014. Number of simulations: 1.75 million.

The capacity shortage in Norway occurring in Data16 (table 5) is no longer there because in Data9 Norway is included as one, single area.

However, there is a capacity shortage in DK2 in 2025, which was not the case for Data16 (this, however, can be explained by statistical uncertainty). The relatively low probability of capacity shortages in Denmark in the regional calculation contrasts with the calculations for Denmark alone. This is discussed below.

Figure 13 shows the installed capacity available through interconnectors as a percentage of peak electricity demand in the countries considered. Denmark's capacity available through interconnectors is considerably higher than for the other countries considered (relatively speaking). This explains how Denmark can have a relatively good capacity adequacy when even though domestic capacity is relatively limited.

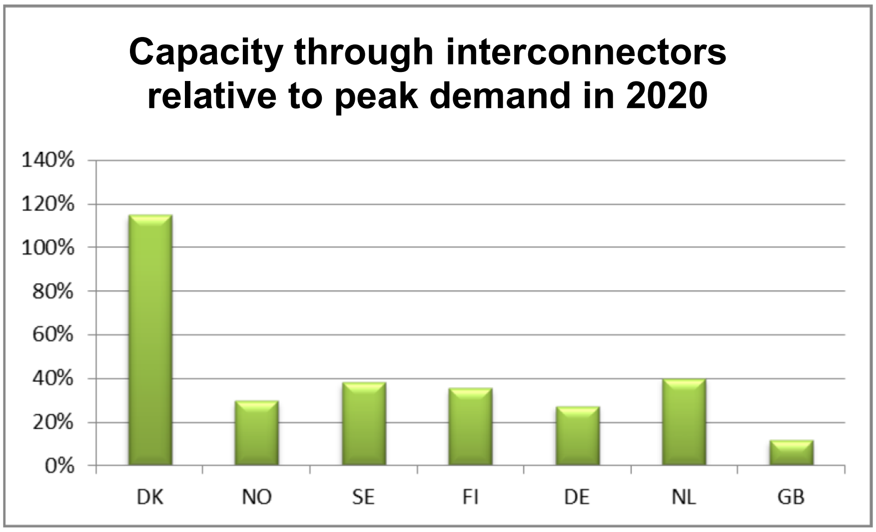

Figure 14 Installed capacity through interconnectors 2020 as a percentage of peak demand for the countries considered.

Capacity adequacy 2015 to 2025 (national calculations using Data2)

A number of simulations were run using the Data2 data set and with 2*1000*8760 hours per run, i.e. almost 20 million hours. The calculations were performed with both 2013 and 2014 hourly series.

The calculated capacity shortage rates for the three model years are shown in table 7. Capacity shortages occur in DK2 in all years. In DK1, capacity shortages do not occur until 2030. The calculated outage minutes are partly 'pure LOLP' values, i.e. the probability of capacity shortage multiplied by the number of minutes in a year (without taking into account electricity demand that is curtailed), and partly a number of minutes calculated according to Energinet.dk's methodology, which converts the calculated occurrences of capacity shortages into the probability of total blackouts, expressed as a percentage of the number of large power plants and HVDC connections in operation at the time of the shortage. See Annex A for a more detailed description.

The results in table 7 more or less confirm the conclusion from the Danish power system function analysis. However, the capacity shortage in DK2 is more prominent here, which is due to the lower capacity in the new calculations.

Area	2015	2020	2025
DK1	<~0.1	<~0.1	1.3 / 0.7
DK2	0.27 / 0.15	3.3 / 1.5	29 / 15

Table 7 Simulated rate (minutes/year) of capacity shortages for DK1 and DK2. 2*1000*8760 hours (half with 2013 hourly series; and half with 2014 hourly series). Blue figures are LOLP minutes (rate of capacity shortages). Red figures are EUE minutes (expected unserved energy converted into weighted outage minutes).

The calculated capacity shortages do not exclusively occur during peak load; nor do they exclusively occur during low wind power and photovoltaic power generation. This is illustrated in figure 15, which shows the simulated result of capacity shortages in DK2 in 2020. The simulation was run for 1000 years, i.e. capacity shortages occur on average 0.056 times per year, corresponding to around 3 minutes. The figure shows that the simulated occurrences of electricity shortages occur at electricity demands between 45% and 90% of annual peak demand. Wind power generation is between 0% and around 40% of annual peak demand. Average wind power generation is around 35% of annual peak demand, so wind power generation during capacity shortages is typically considerably 'below average', but it can be slightly above average. During situations with capacity shortages, photovoltaic power generation can be both very high and very low. This is related to the fact that photovoltaic solar modules 'contribute' relatively little and, therefore, only have minor significance for capacity shortages in DK2 in 2020. Furthermore, the simulated capacity shortages occur throughout the year and not just during the winter.

The figure illustrates why traditional methodologies using capacity balances (which involve comparing installed capacity (typically weighted) with annual maximum peak demand) are ill suited to forecast capacity adequacy.

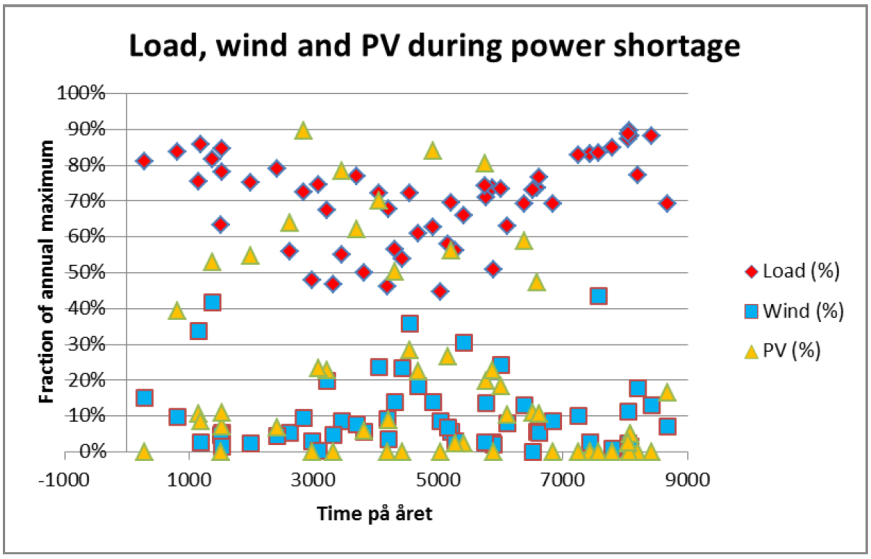

Figure 15 Electricity demand, wind power generation and photovoltaic power generation in DK2 2020 during periods with capacity shortage (1000 years of simulation runs).

Figures 16 and 17 below illustrate in two different ways the capacity situation in DK1 and DK2 in 2020. Figure 16 shows the installed capacity including interconnectors, and including wind and solar power at their fullest capacity. This calculation seems to show a considerable overcapacity, however the various types of capacity do not all have the same significance for security of supply. Figure 17 shows instead the average capacity surplus. Here, the capacity of each plant has been included at what is available on average across the hours in the year, and the total is compared with the annual peak demand. None of the figures, however, say anything explicitly about capacity adequacy.

Figure 18 shows the percentage of time when DK1 and DK2, respectively, are unable to meet their own electricity demand, i.e. the percentage of time when the generation capacity available in an area is less than the electricity demand in the same area. Increased import dependence is not in itself a problem for capacity adequacy. For example, this is evident from the fact that DK1 has a slightly higher import dependence than DK2, although DK1 has better capacity adequacy than DK2, see table 7.

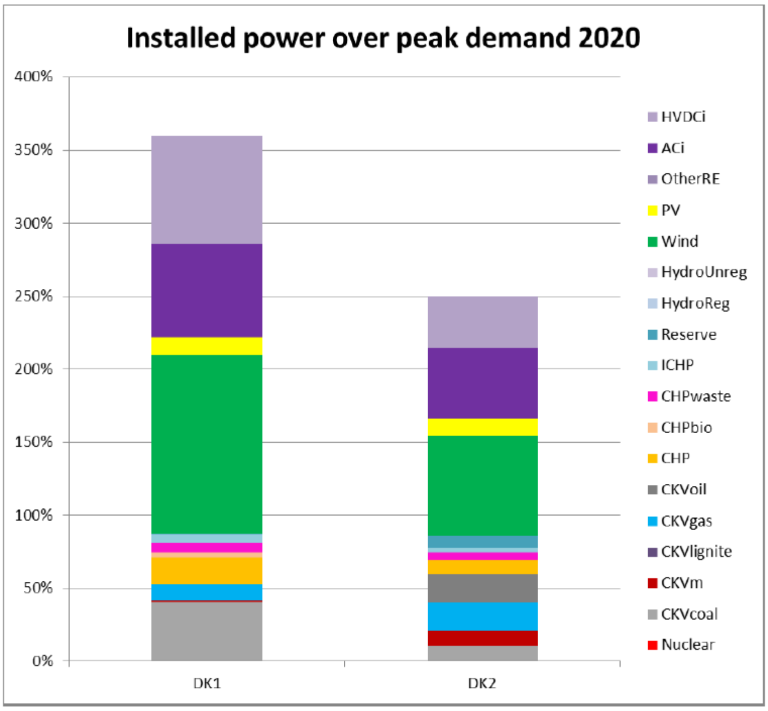

Figure 16 Installed capacity in DK1 and DK2 2020 as a percentage of annual peak demand (100%).

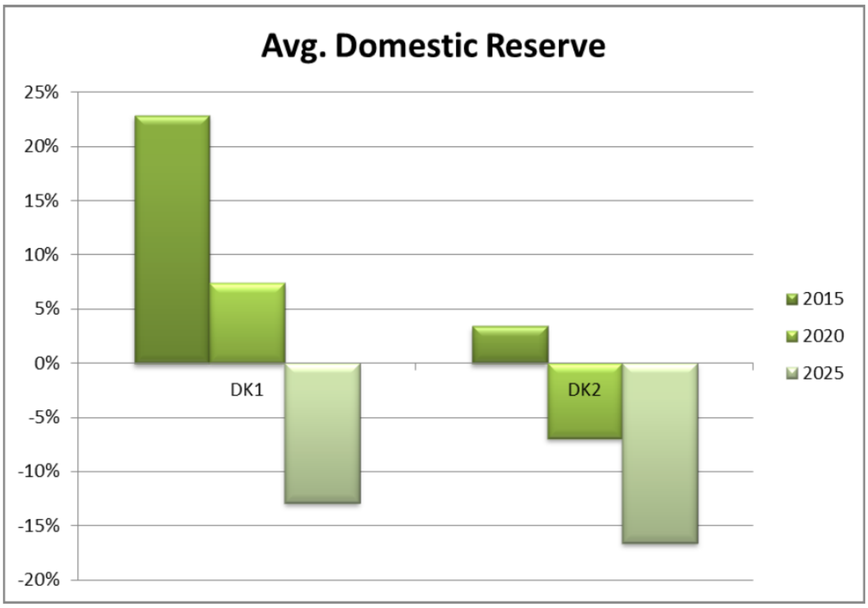

Figure 17 Average capacity reserve in DK1 and DK2 over time as a percentage of peak demand.

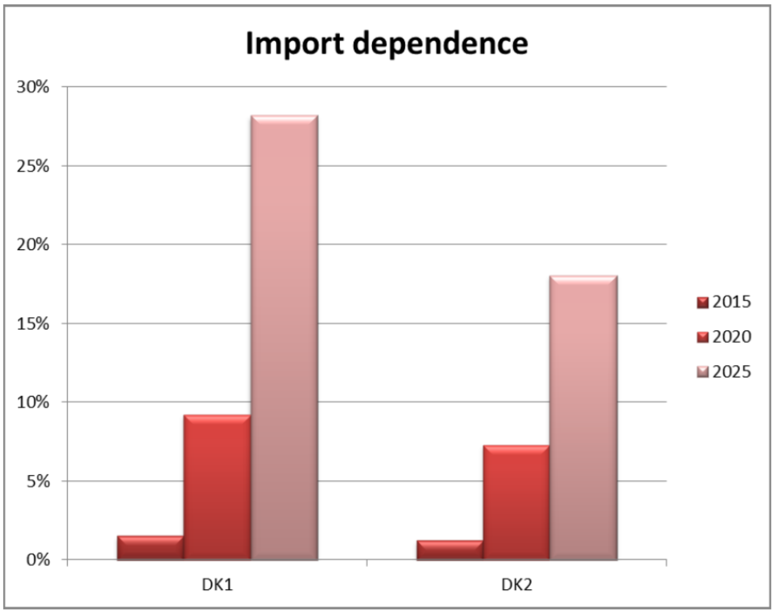

Figure 18 Import dependence.

The development in the Danish capacity mix 2015 to 2025 in absolute terms is illustrated in figures 19 to 21.

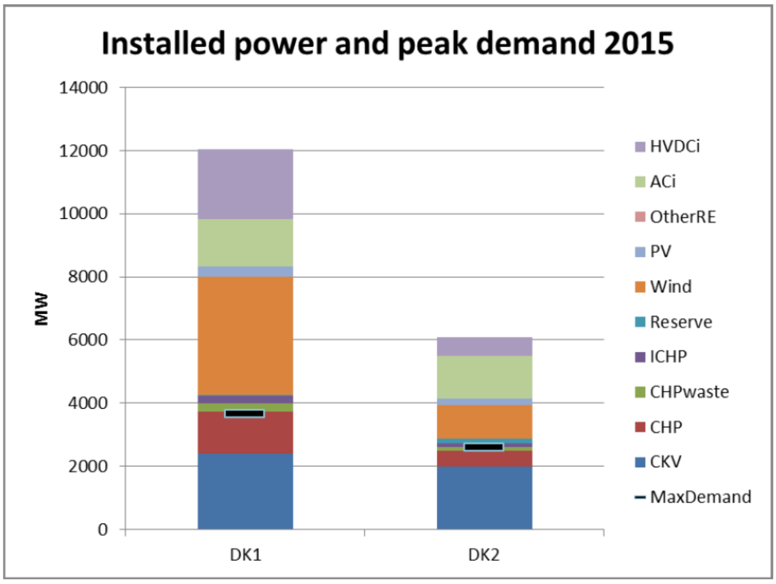

Figure 19 Installed capacity and peak demand 2015.

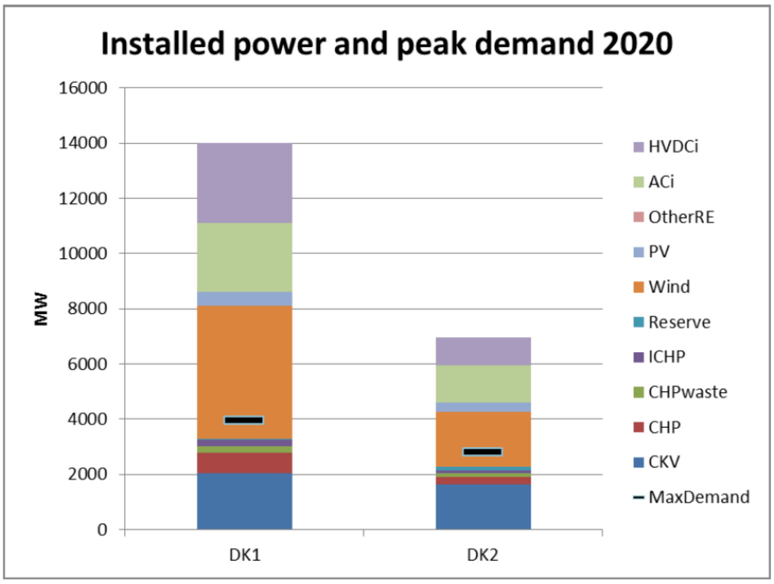

Figure 20 Installed capacity and peak demand 2020.

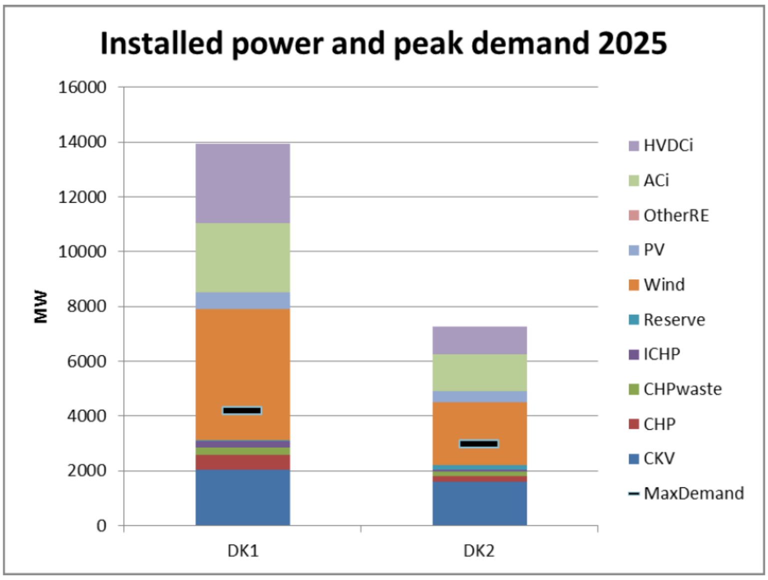

Figure 21 Installed capacity and peak demand 2025.

Comparison of regional and national calculations of capacity shortages

The calculations using Data16, Data9 and Data2 should give approximately the same probability of capacity shortage in DK1 and DK2, if all of the data sets are 'correct'.

However, the calculations using Data16 and Data9 show lower capacity shortage rates in Denmark than the national calculation using Data2.

This may suggest that the CF level, in general, has been set too high. In other words, capacity adequacy may be better in DK1 and DK2 than appears from the national calculation. A possible explanation for this is that the geographical spread of wind power variations etc. may have a greater positive effect than assumed. However, so far this is only a hypothesis.

This explanation assumes, however, that the capacity situation in Denmark’s neighbouring countries has been correctly assessed. Considerably lower capacity expansion in neighbouring countries than assumed in the baseline estimation could therefore have great significance for Danish capacity adequacy (see the sensitivity analyses below).

The regional calculations have been performed assuming that capacity surplus in one country is made available to neighbouring countries without any form of hindrance (provided there is enough transmission capacity in the individual hour). This means that the market or other factors pose no hindrance to exploitation of the capacity. Such market restraints do however exist in practice, and, therefore, more modest country failure assumptions may be well-advised.

Sensitivity calculations

Several sensitivity calculations have been conducted. The majority of these calculations have been performed as national calculations, primarily due to the calculation time in SISYFOS, which is considerably shorter when the national data set is used.

Rapid shutdown of capacity abroad (regional calculation)

For use in the analysis, the Danish Energy Association has provided a data set of capacity trends in Denmark's neighbouring countries. This data set is based on the Platts database of existing power plants in Europe, combined with assumptions regarding the lifespan of the different types of power plant (see the section on generation capacity). The Platts data set differs from the ENTSO-E data, especially as in around 2025 there is significantly lower thermal capacity in Germany (71 GW compared with 99 GW), and in the Netherlands (21 GW compared with 27 GW). The Platts data set does not reflect the Danish Energy Association's expectations; it is used solely to illustrate the extreme situation in which Denmark's thermal capacity is neither developed nor renovated, and instead only wind and solar capacity are expanded.

The present sensitivity calculation shows a pronounced LOLP increase in DK1, Germany and the Netherlands (see Table 8). An increase in LOLP is also seen in DK2 and SE4. It is likely that the pronounced difference between the capacity in DK1 and in DK2 is because, in 2025, DK1 has 3200 MW exchange capacity with Germany and the Netherlands, whereas DK2 has exchange capacity of only 1000 MW. This explains why a poor capacity situation in Germany will affect DK1 first.

Even though it is unlikely that Germany will allow such a pronounced capacity shortage to occur, the calculation illustrates that capacity trends in Germany and some other countries should be monitored closely. The Netherlands has set a statutory limit for expected capacity shortages at 3 hours (180 minutes); this entails that an expected value of 352 minutes would require action, i.e. a shortage lasting 352 minutes would not be allowed to happen in reality.

	2020 baseline	2020 DE	2025 baseline	2025 DE
DK1	<~0.7	<~0.6	<~0.7	119
DK2	<~0.7	<~0.6	0.6	1.1
NO	<~0.7	<~0.6	<~0.7	<~1.3
SE12	<~0.7	<~0.6	<~0.7	<~1.3
SE3	<~0.7	<~0.6	<~0.7	<~1.3
SE4	<~0.7	<~0.6	<~0.7	1.6
FI	<~0.7	<~0.6	<~0.7	<~1.3
DE	<~0.7	<~0.6	<~0.7	2145
NL	<~0.7	<~0.6	<~0.7	352

Table 8 Calculated difference in simple LOLP (minutes/year) with baseline estimation and no thermal expansion, respectively, in Germany and the Netherlands, etc.

Shutdown of Ringhals 1 and 2 earlier than anticipated (regional calculations)

On 28 April 2015, Vattenfall announced that it would shut down the two nuclear power plants Ringhals 1 and 2 earlier than anticipated, and the shutdown date was moved from 2025 to somewhere between 2018 and 2020. The baseline estimation includes Ringhals 1 and 2 for the year 2020, but not for 2025. A sensitivity calculation has been performed for 2020 in which Ringhals1 and 2 have been shut down.

This calculation does not show any capacity shortage in Denmark. The calculation is based on 0.6 million time steps, and, due to the statistical uncertainty, it is therefore only possible to determine with 90% certainty that LOLP is less than 1.9 minutes.

Revised probability of failure of supply by international suppliers (national calculations)

The most uncertain assumptions probably include those regarding the probability of a 'country failure' (CF). Due to this uncertainty, a sensitivity calculation has been conducted in which the probabilities are halved (½*CF) and doubled (2*CF). The calculation is for 2020 (table 9) and for 2025 (table 10).

(minutes/year 2020)	Initial calculation	½*CF	2*CF
DK1	<~0.1	<~0.1	<~01
DK2	3.3	1.5	5.2

Table 9 The impact of revised assumptions concerning 'country failure' 2020. 2*1000*8760 time steps. Pure LOLP minutes.

(minutes/year 2025)	Initial calculation	½*CF	2*CF
DK1	1.6	0.3	2.7
DK2	29	11	35

Table 10 The impact of revised assumptions concerning 'country failure' 2025. 2*1000*8760 time steps. Pure LOLP minutes.

Probability of failures on interconnectors (national calculations)

The initial calculation is based on 8% downtime for HVDC interconnections and 5% downtime for AC interconnections. These downtimes reflect technical availability. A sensitivity calculation based on double the failure rates (16% for HVDC connections and 10% for AC connections) have been conducted. There is no reason to expect such high failure rates; however the sensitivity calculation could illustrate the consequences of more frequent shutdowns of the connections due to market conditions. Table 11 shows the result. As can be seen, the downtime for the power lines greatly affects the expected capacity shortage.

(minutes/year 2020)	Initial calculation	2*failure factor for interconnectors
DK1	<~0.02	0.24 / 0.18
DK2	3.3 / 1.5	10 / 5.9

Table 11 Sensitivity calculation for 2020 with twice the failure factor for interconnectors Blue figures are simple LOLP minutes.Red figures are EUE minutes.

Year of shutdown of large-scale plants (national calculations)

A sensitivity calculation for 2020 based on earlier shutdown of large-scale capacity in Denmark has been conducted. The calculation assumes replacement of Esbjergværket with a 60 MW biomass-fueled back-pressure unit, corresponding to a loss of capacity of 340 MW, and shutdown of block 21 of Kyndbyværket before 2020, corresponding to a loss of capacity of 260 MW. The likelihood of this in reality has not been considered; figures merely reflect the hypothetical consequences of shutting down more capacity.

The calculation (see table 12) shows reduced capacity adequacy in DK2, whereas the same reduced capacity adequacy is not seen in DK1.

(minutes/year 2020)	Initial calculation	Shutting down 600 MW large-scale capacity
DK1	<~0.02	<~0.02
DK2	3.3 /1.5	8.8 / 4.5

Table 12 Consequences of shutting down more large-scale capacity. Blue figures are simple LOLP minutes. Red figures are EUE minutes.

Small-scale CHP plants shut down earlier than anticipated (national calculations)

The baseline estimation is based on the assumption that about 50% of natural-gas-fired small-scale CHP plants will be decommissioned by 2020 due to cancellation of the basic amount at the end of 2018. A sensitivity calculation (worst-case scenario) has been performed based on the shutdown of all natural-gas-fired CHP plants, that is, the shut down of an additional 1000 MW in 2020 (730 MW in DK1 and 270 MW in DK2). The effects of this are shown in table 12 (2020) and table 14 (2025). The figures show that the shutdown has the greatest impact in 2025, at which time the system will be under greater pressure.

(minutes/year 2020)	Baseline estimation	Shutdown of all NG SCHP
DK1	<~0.02	<~0.02
DK2	3.3 / 1.5	3.9 / 2.9

Table 13 Impact on capacity adequacy in 2020 of shutting down all natural-gas-fired small-scale CHP plants. Blue figures are simple LOLP minutes.Red figures are EUE minutes.

(minutes/year 2025)	Baseline estimation	Shutdown of all NG SCHP
DK1	1.3 / 0.7	5.8 / 7.2
DK2	29 / 15	42 / 27

Table 14 Impact on capacity adequacy in 2025 of shutting down all natural-gas-fired small-scale CHP plants. Blue figures are simple LOLP minutes.Red figures are EUE minutes.

Decoupling the co-generation of heat at small-scale plants (national calculation)

The baseline estimation assumes that the natural-gas-fired small-scale CHP plants are highly linked to co-generation of heat. In recent years, following the entry of gas-fired small-scale plants to the electricity market, electricity generation has in general decreased due to the less favourable relationship between the selling price for electricity and the buying price for gas. If it is likely that generation from these plants will be limited at all events, co-generation of heat by these plants can be reduced and instead the plants could be included with more reserve power and regulating power.

A sensitivity calculation has been conducted in which co-generation of heat by natural-gas-fired small-scale CHP plants is reduced from 70% to 10%. The calculation has been based on figures for 2025 so as to include the effect on DK1 (the majority of plants are located in DK1). The results of this calculation can be seen in table 15. There is a clear, positive effect on capacity adequacy if the capacity in natural-gas-fired small-scale plants is released from the link to heat production. In relative terms, the effect of this would be greatest in DK1 where the majority of these plants are located.

(minutes/year 2025)	Baseline estimation	Reduced co-generation of heat
DK1	1.6	0.48
DK2	29	23

Table 15 Impact of reduced co-generation of heat on natural-gas-fired small-scale CHP plants. Pure LOLP minutes.

Additional Great Belt connection (national calculations)

Because the calculations in this report show that the capacity adequacy in DK2 is significantly lower than in DK1, a new, additional Great Belt connection is worth considering so as to better exploit DK1's capacity in DK2. Therefore a sensitivity calculation with twice the capacity in the Great Belt connection before 2025 has been conducted; i.e. the calculation is based on there being two independent connections of 600 MW in 2025. However, these calculations do not reflect the advisability of such a link.

The results of the calculation are in table 16. The table shows that an additional connection would have a substantial impact on capacity adequacy in terms of a slight improvement in DK1 and a significant improvement in DK2. This difference between DK1 and DK2 is due to the fact that, in by far the majority of cases, the (calculated) capacity shortage is either due to failure in the Great Belt connection, or because the connection is not large enough to even-out the capacity shortage between DK1 and DK2.

(minutes/year 2025)	Baseline estimation	Additional Great Belt connection
DK1	1.3	1.0
DK2	29	3.3

Table 16 Impact of an additional Great Belt connection in 2025. 2*1000*8760 time steps. Pure LOLP minutes.

Electricity link to the United Kingdom (national calculations)

In collaboration with National Grid (the TSO in United Kingdom), Energinet.dk is planning to establish a cable between Jutland and the southern part of England (the Viking Link). The plan is to establish a direct-current connection ranging between 1,000 MW and 1,400 MW.

A sensitivity calculation has been conducted based on establishment of a 1400 MW link between DK1 and the United Kingdom in the period 2020 to 2025. The results of this calculation are in table 17. However, these calculations do not reflect the advisability of such a link.

(minutes/year 2025)	Baseline estimation	With a link to the United Kingdom
DK1	1.3 / 0.7	0.06 / 0.08
DK2	29 / 15	18 / 12

Table 17 Impact on capacity adequacy of a 1400 MW link to the United Kingdom before 2025. Blue figures are simple LOLP minutes.Red figures are EUE minutes.

Thus, capacity adequacy in DK1 will improve, but from an already high level. Capacity adequacy in DK2 will also improve in this scenario, because, in situations where DK1 does not have high enough surplus to compensate for any deficit in DK2, capacity may be provided from Great Britain.

The impact of wind power on capacity adequacy (national calculations)

A calculation has been conducted taking into account an increase in wind-power capacity in Denmark in 2025. The objective of this calculation is to examine whether increasing wind power in itself will increase capacity adequacy. The calculation is based on an additional 2 TWh wind power in both DK1 and DK2, corresponding to approx. 500 MW from offshore wind installations in each area or approx. 700 MW from onshore wind installations. The result of the calculation is in table 18. Increasing wind power will have a positive effect on capacity adequacy, albeit a relatively modest effect.

(minutes/year 2025)	Baseline estimation	+4 TWh wind power
DK1	1.3 / 0.7	1.2 / 1.4
DK2	29 / 15	24 / 14

Table 18 Impact of increased wind power on capacity adequacy. Blue figures are simple LOLP minutes. Red figures are EUE minutes.

Table 19 below shows the result of a (very hypothetical) calculation in which all Danish wind power has been removed in 2025. The calculation demonstrates how wind power that is already installed and wind power agreed in the 2012 Energy Agreement contribute to capacity adequacy. As is seen, wind power has contributed, and contributes, significantly to capacity adequacy.

(minutes/year 2025)	Baseline estimation	Without wind power
DK1	1.3 / 0.7	14 / 17
DK2	29 / 15	156 / 103

Table 19 The impact of removing all Danish wind power 2025 Blue figures are simple LOLP minutes. Red figures are EUE minutes.

It is assessed (no calculations) that the onshore/offshore mix of Danish wind power does not play a significant role with regard to capacity adequacy. Geographical distribution is assessed to play a greater role.

Increased demand side flexibility (national calculations)

Voluntary curtailment from the grid may contribute in the long term to ensuring capacity adequacy. Figures 22 and 23 show the estimated capacity shortage in the baseline estimation ranked by size. In DK1 there were 22 occurrences of capacity shortage, and in DK2 there were approximately 500 occurrences of capacity shortage in the approximately 20 million simulations conducted. The results show that flexible demand at a level of 200 MW in each area could potentially eliminate 50% of capacity-shortage occurrences and reduce the scope of other incidents. However, such a development would require perfect curtailment of demand, which seems improbable in reality.

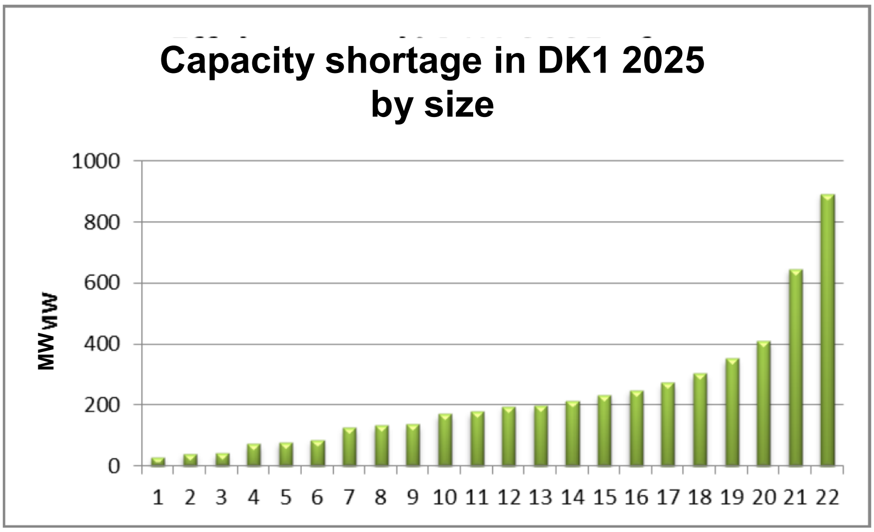

Figure 22 Calculated capacity shortage in DK1 2025 by size 2*1000*8760 simulations.

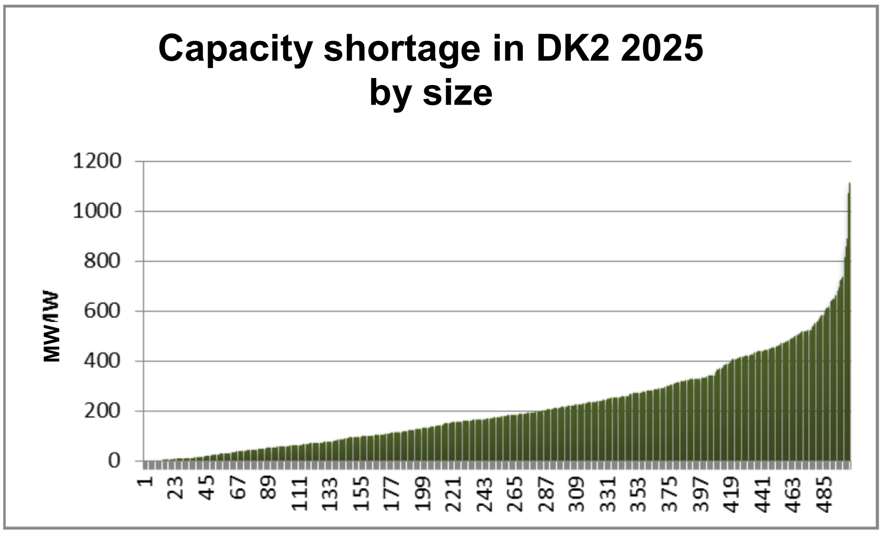

Figure 23 Calculated capacity shortage in DK2 2025 by size 2*1000*8760 simulations.

Effect of using different time series (national calculations)

The calculations presented above are based on time series from 2013 and 2014. It has proven difficult to obtain concurrent time series for previous years for electricity demand, wind power and photovoltaic power generation for all the countries included in the analysis. A sensitivity calculation for Denmark alone has been conducted to examine the effect of using time series from other years, including 2010, which was a relatively cold year.

Figure 24 illustrates the number of expected outage minutes based on time series from 2010, 2011, 2012, 2013 and 2014, respectively. As can be seen, the 2010 time series yields a slightly higher number of outage minutes than the 2013 and 2014 series, whereas the 2011 and 2012 series yield a slightly lower number of outage minutes. However, there is no significant difference between the time series.

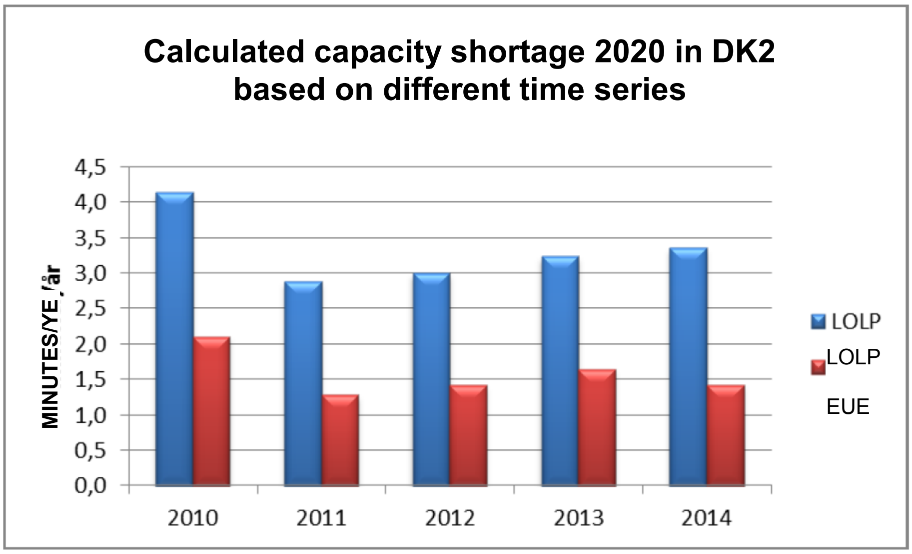

Figure 24 Calculated capacity shortage based on different time series. 1000*8760 simulations.

Annex A. The SISYFOS model

A.1 Introduction

The SISYFOS model was developed in 2012 to simulate the security of supply in an electricity system[4] with or without a grid. Based on data for a number of nodes that consume electricity and/or for power plants/wind power plants/photovoltaic solar modules as well as a number of interconnectors, power lines and transmission substations between these nodes, the expected unserved energy and the probability of electricity shortages and a number of other things are calculated.

The model was programmed using VBA in Excel and uses Monte Carlo simulation of the available capacity of plants and power lines as well as linear programming (LP) to calculate generation in nodes and flow in the grid.

SISYFOS comprises two Excel files:
the Sisyfos.xlsm model file containing the VBA code and the LP problem,
and a data file containing input data and results.

Energinet.dk has previously used an early version of SISYFOS, which did not include grids, to develop the so-called FSI model. Both FSI and SISYFOS were used in the two 2014 analyses "The electricity grid. Analysis of Danish power system function" and "Analysis of scenarios". In addition, Ea Energianalyse borrowed SISYFOS in 2013/14 to conduct an analysis of the security of supply of the Lithuanian power system.

A.2 Definition of security of supply and capacity adequacy

Security of supply is defined as the probability that electricity is available when demanded by consumers. Capacity adequacy is an element of this and it can be defined as the probability that there are enough plants and power lines in the system. When describing the capacity adequacy of an electricity system, the two terms LOLP and EUE are used[5]:

- LOLP (Loss of Load Probability) is the probability that the electricity available cannot match consumer demand. LOLP does not distinguish between a shortage of 1 MW or 1000 MW. If there is one 1 MW shortage per 10,000 hours, the LOLP value will be the same as when there is one 1000 MW shortage per 10,000 hours. LOLP can be converted into number of minutes/year by multiplying by the number of minutes per year. An LOLP of e.g. 10^{-5} corresponds to 5.3 minutes/year. This is also referred to as the LOLE (Loss Of Load Expectation).
- EUE (Expected Unserved Energy) is the calculated expected value that includes an expected probability of a system collapse (blackout) when there is a capacity shortage. This methodology was developed by Energinet.dk and is incorporated in SISYFOS in the following way: When there is a capacity shortage, the numbers of large plants (more than 125 MW) and HVDC connections in operation are counted, that is the 'ancillary service units'.

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[4] SISYFOS is an acronym for the Danish " SImulering af SYstemers FOrsyningsSikkerhed" (simulation of the security of supply of systems).

[5] SISYFOS also calculates the amount of energy that is not supplied assuming that all capacity shortage situations can be controlled. That is, if there is a shortage of 200 MW, 200 MW can be decoupled without causing any disturbances. Therefore, in practice, this calculation underestimates the occurrence of capacity shortages, as a minor capacity shortage in some situations can entail a larger shortage - and possibly a complete blackout.

It is assumed that each of these plants may experience a 5% increase in the probability of failure, because the electricity system is under pressure. If at least one of these units experience failure, a three-hour blackout is assumed. Thus the calculated amount of energy will be three-times the total electricity demand in the hour with the capacity shortage. This calculation is performed for each electricity area. EUE can be converted into number of minutes/year by dividing EUE by the total annual electricity demand and multiplying this number by the number of minutes in a year.

A.3 Mathematical formulation of the problem

Assume a power system with n nodes: 1, ... , n. Electricity demand in each hub equals D_i (MW). D_i is assumed to be determined as a function of time using a load curve.

Each individual hub[6] has its own available electricity generation capacity, P_i (MW). P_i is assumed to be determined as the installed capacity in one or more units multiplied by a failure factor and an audit factor. Whether or not a unit is subject to failure, or whether it is experiencing downtime due to an audit, is determined using Monte Carlo simulation and an audit model. The actual production in the hub at a given time is X_i (MW).

Failure is a random incident. That is, the probability of a plant experiencing a one-hour failure does not increase if the same plant experienced a failure in the preceding hour. Therefore, in the model, failure incidents are independent of one another. However, this does not affect the overall probability of capacity shortage.

Wind power, photovoltaic power and run-off-river hydropower generation is determined on the basis of annual generation and an historical time series. See also Annex B.

Between every two nodes i and j, at any given time the transmission capacity of the grid is C_{ij} (MW). C_{ij} is determined at every time step as the installed capacity multiplied by a failure factor and an audit factor[7]. Whether there is failure on a power line or downtime is due to an audit is determined using the Monte Carlo simulation. Transmission capacity may vary depending on the direction of transmission. The actual flow in the grid at any given time is F_{ij} (MW).

A link to an electricity area that lies outside the model is specified as a 'power plant' with the capacity available through the power line and a probability of failure corresponding to the probability of failure of the power line. In addition, there is a probability that the country responsible for the power line experiences failure.

Thus, the task is to determine X_i so that unserved energy LOE = $\sum_i(D_i - X_i - \sum_j F_{ji})$ is minimised. As $\sum_i\sum_j F_{ij} = 0$ and as $\sum_i D_i$ is a constant for a given time step, it is sufficient to minimise $\sum_i(-X_i)$, which is the same as **maximising** $\sum_i X_i$, that is maximising the total electricity generation. The overall problem can be expressed mathematically as:

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[6] Note that a hub can be a delivery point in e.g. a 150 kV grid or an entire country, or a large electricity area (e.g. west Denmark or Sweden).

[7] An audit plan can be prepared or (alternatively) random audits can be included in the model. If this is done, the probability of a plant being audited at time t (1 ....8760) is given as 1 - r + r * Cos(t/8760*2π), where r is the audit rate.

Maximise $Z = \sum_i X_i$ with the sub-conditions

1. **$0 \leq X_i \leq P_i$**
2. **$-C_{ji} \leq F_{ij} \leq C_{ij}$**
3. **$X_i + Z_j F_{ji} \leq D_i$**

That is maximise electricity generation while maintaining the restraints from demand as well as the available capacity of plants and power lines. This is a linear programming problem with up to n(n+1) sub-conditions in the standard situation[8]. In practice, the number of sub-conditions will be considerably smaller because not all nodes produce energy nor are all nodes in a grid connected.

The equation system is solved in SISYFOS using OpenSolver/QuickSolve; an open source add-in that is much faster than Excel's standard solver. Moreover, the calculation time can be reduced considerably by using an intelligent initial guess with regard to how much electricity is transmitted between the different electricity areas.

SISYFOS solves the grid problem by providing a ***possible*** solution to the grid flows. That is, it does not offer an 'optimal' or 'fair' solution. This means that situations may occur where one hub seems to have better capacity than another, merely because the one hub is always calculated first by SISYFOS.

In principle there should be a connection between the calculated probability for capacity shortage today and the actual measured shortage. A calculation for 2015 should therefore provide a probability for the capacity shortage in the range of 10^{-6} (½ minute/year) or smaller, because so far no capacity shortage has yet been observed.

Statistical uncertainty

In general, the results of the calculations include a statistical uncertainty. That is, repeating the calculation using the same data set will not yield the same result, due to the probabilistic approach.

The statistical uncertainty can be illustrated by using the following - somewhat simplified - method: Assume probability p for capacity shortage in a single time step, and assume that n time steps are simulated. This gives the probability that e occurrences of capacity shortage occur, based on the binomial distribution

$$\text{Prob.}(e) = K(n,e) \times p^{e} \times (1-p)^{n-e}$$

where K(n,e) is the number of possibilities for extracting e from a population of n.

When n = 100 x 8,760 and $p = 2.6 \times 10^{-6}$ the probability distribution will be as is seen in figure 25.

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[8] n sub-conditions from the limits on generation (1), n (n-1) from the limits on power lines (2) and n from the hub condition (3).

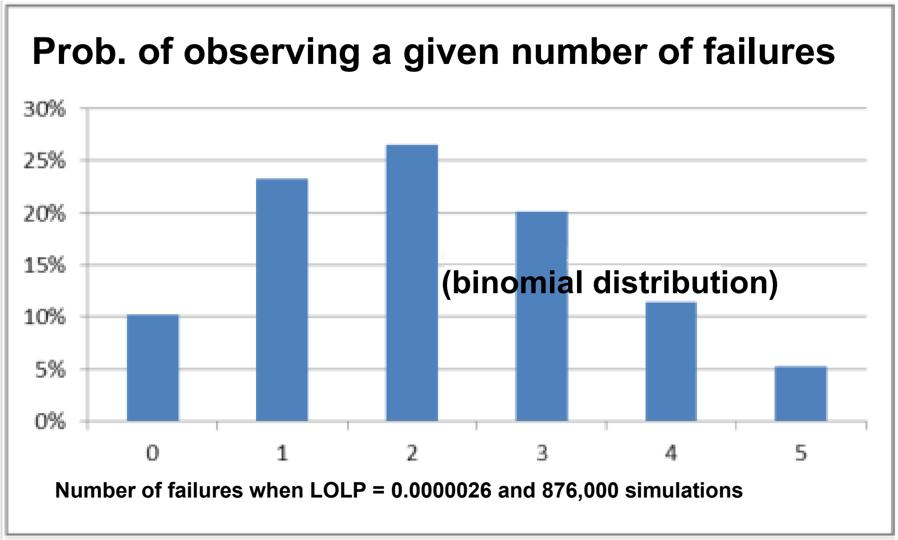

Figure 25 Illustration of binomial distribution.

That is, if 100 x 8,760 hours have been simulated showing no occurrence of capacity shortage, this is a 'fairly certain' indication that LOLP is less than 2.6 x 10^{-6} (1.4 minutes per year), in that, with a 90% probability, the simulation should have shown at least one occurrence of capacity shortage.

When n = 100 x 8,760 and p = 8 x 10^{-7}, the probability distribution will be as in figure 26.

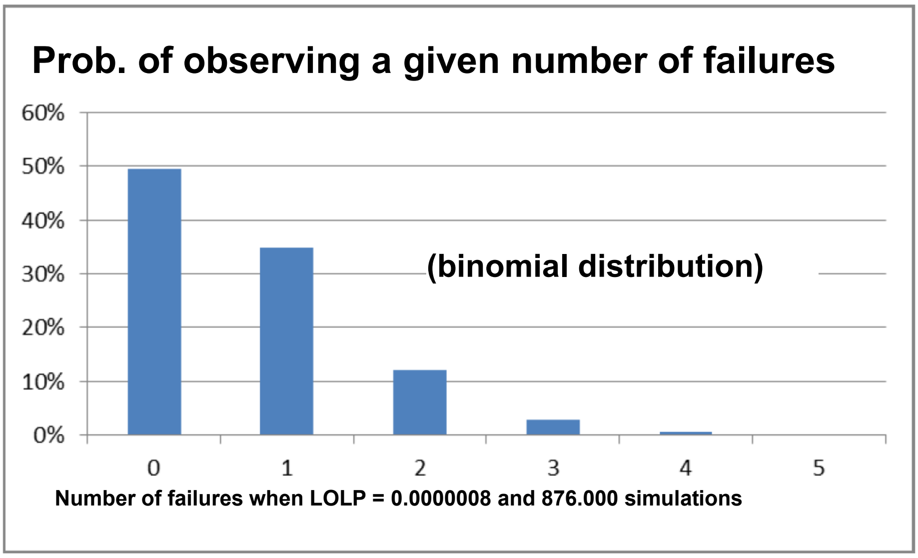

Figure 26 Illustration of binomial distribution.

That is, if 100 x 8,760 hours have been simulated showing no occurrence of capacity shortage, LOLP is 'probably' less than 8 x 10^{-7} (0.4 minutes per year), in that the simulation has a 50% certainty of showing at least one occurrence of capacity shortage.

In reality, p is the same in all time steps (highest during periods of high demand and low wind power). This means that the above is very simplified.

A.4. Input data for SISYFOS

Input data are in an Excel file and include a number of pages:

- Hub data can be found in the data file on the page **Nodes**. Data comprise name of hub, number and electricity consumption, etc. In addition, the page includes a matrix GTR that lists a guess for electricity transmission between the electricity areas. If the guess is good, the calculation will be much quicker because the need for the solver is much smaller. Preparing a GTR can help ensure that the average capacity surplus after transmission is as close as possible to being the same in all areas.
- The grid (interconnectors, lines and transformers) can be found on the **Lines** page. Data comprises hub names and numbers for the beginning and end of the lines, capacity in each direction, downtime and number of cables per line.
- Plants can be found on the page **Plants**. Data comprises name of plant, name and node number, installed capacity, type of plant, planned and unplanned outage planned outage priority and two factors that describe co-generation of heat.[9] Moreover, any coupled probabilities can be specified. For example, 'country failures' (the probability of failure to supply by a country not included in the model).
- Standardised electricity demand variations, wind power variations, photovoltaic power variations and variations for run-off-river hydropower are on the TVAR page.
- The hourly temperature is on the **Temp** page.
- The results of the calculation are posted on **Result**.
- The grid can be drawn. This can be done on the **GridDrawing** page. The coordinates specified on the Nodes page are used when drawing the grid. See the example in figure 27.
- Other data, graphs, etc. can be found on the **OtherData** page and the subsequent pages.

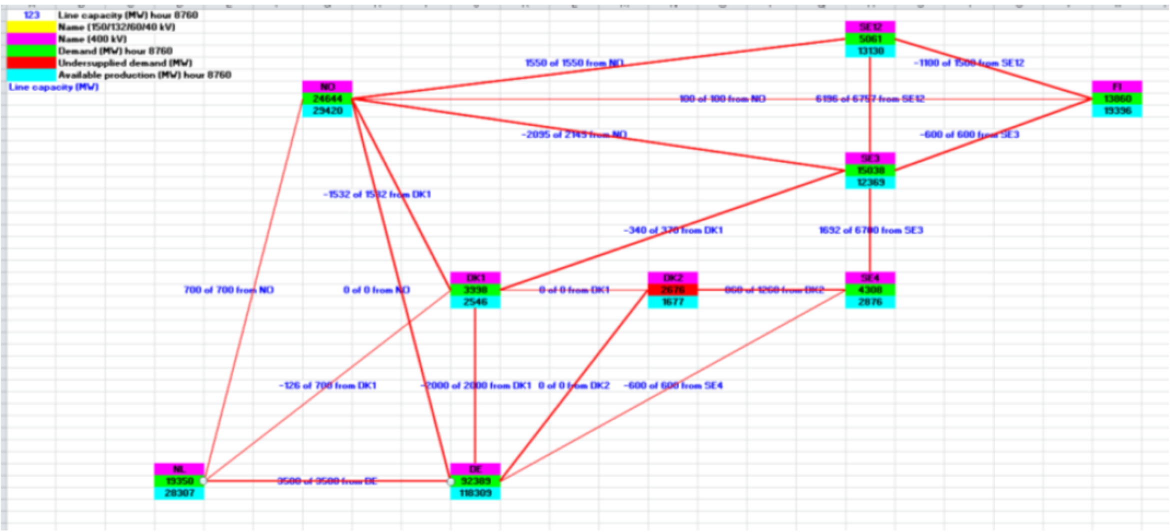

Figure 27 Grid diagram from SISYFOS of capacity shortage in DK2 based on calculation using Data9.

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[9] Co-generation of heat is modelled using two parameters: DHconst and DHvar. When calculating the available capacity of a plant at a given time, the following factor is used: DH = DHconst + DHvar * (MaxTemp -Temperature) / (MaxTemp - MinTemp). The temperature is taken from TRY (reference year). For plants with no co-generation of heat, DHconst = 1 and DHvar = 0.

Annex B. Hourly series

Standardised historical hourly values are used for electricity demand, wind power generation, photovoltaic power generation and run-off-river hydropower. Hourly values are given in MW per TWh annual demand or annual generation. Hourly values are given in Danish winter time for 2013 and 2014.

All the time series used in one run are from the same year. In a few cases, time series were not available. In these cases, the approximation assessed to be the most representative was used.

This means that time series for wind power in Norway are missing; instead time series for wind power in DK1 were used. Similarly, time series for wind power in Finland for 2014 are also missing; time series for wind power in Sweden were used instead. Finally, time series for wind power in the Netherlands are also missing; time series for wind power in Germany were used instead.

For photovoltaic solar modules, there are only time series for Sweden, Germany and Denmark in 2014. A synthetic time series was used in the calculation for Denmark and Sweden 2013. Photovoltaic solar modules were not included in the calculations for the United Kingdom, Finland and Norway, therefore time series from these countries are not necessary.
The approximations mentioned above underestimate the 'evening-out' of wind and solar power across larger geographical areas, and thus overestimate the probability of capacity shortage.

Sources for the hourly variations comprise market data from Energinet.dk, ENTSO-E's data portal, www.pfbach.dk and the Danish Energy Association.

There is a strong correlation between electricity demand in DK1 and DK2. In addition, there is a relatively strong correlation between electricity demand in DK1 and in Sweden and the Netherlands, whereas the correlation between demand in Norway, Finland and the United Kingdom is slightly weaker. See figures 28 and 29.

Wind power generation in DK1 correlates strongly with DK2, moderately with Germany and relatively weakly with the United Kingdom and Finland. See figures 30-33.

Correlation between photovoltaic power generation in DK1 and Germany is strong. See table 20.

	Consumption 2013	Consumption 2014	Wind 2013	Wind 2014	Solar 2013	Solar 2014
DK1	100%	100%	100%	100%	N/A	88%
DK2	96%	96%	82%	84%	N/A	89%
DE	90%	93%	62%	61%	100%	100%
NOR	71%	67%	N/A	N/A	N/A	N/A
SWE	81%	80%	65%	62%	82%	80%
FIN	71%	67%	34%	N/A	N/A	N/A
NL	92%	91%	N/A	N/A	N/A	N/A
GB	71%	68%	40%	46%	N/A	N/A

Table 20 Correlation[10] between demand and wind time series for DK1 and other electricity areas/countries, and the correlation between German and other photovoltaic power generation.

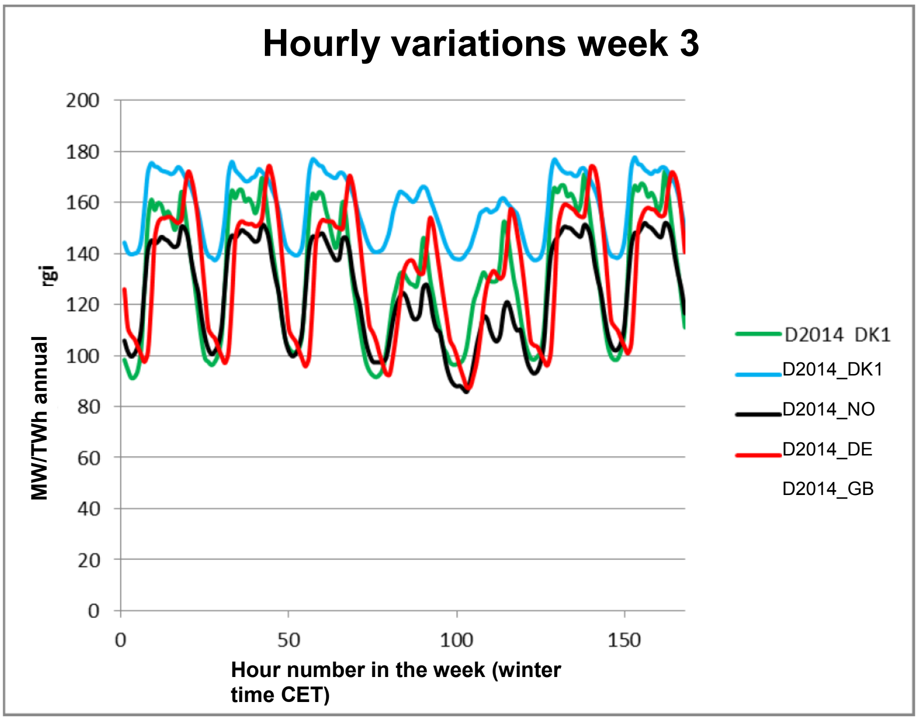

Figure 28 Variation in electricity demand week 3, 2014, in DK1, Norway, Germany and the United Kingdom. The mean value of 1 TWh distributed evenly over the year corresponds to 114 MW/TWh.

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[10] The correlation coefficient between the variables x and y = $\mathrm{Cov}(x,y)/(\mathrm{Var}(x)\mathrm{Var}(y))^{-0,5}$, where Cov(x,y) is the mean value of the sum of the deviation of the x and y values from their mean value, and Var(x) is the mean value of the sum of squares of the deviations of the x values from their average value.

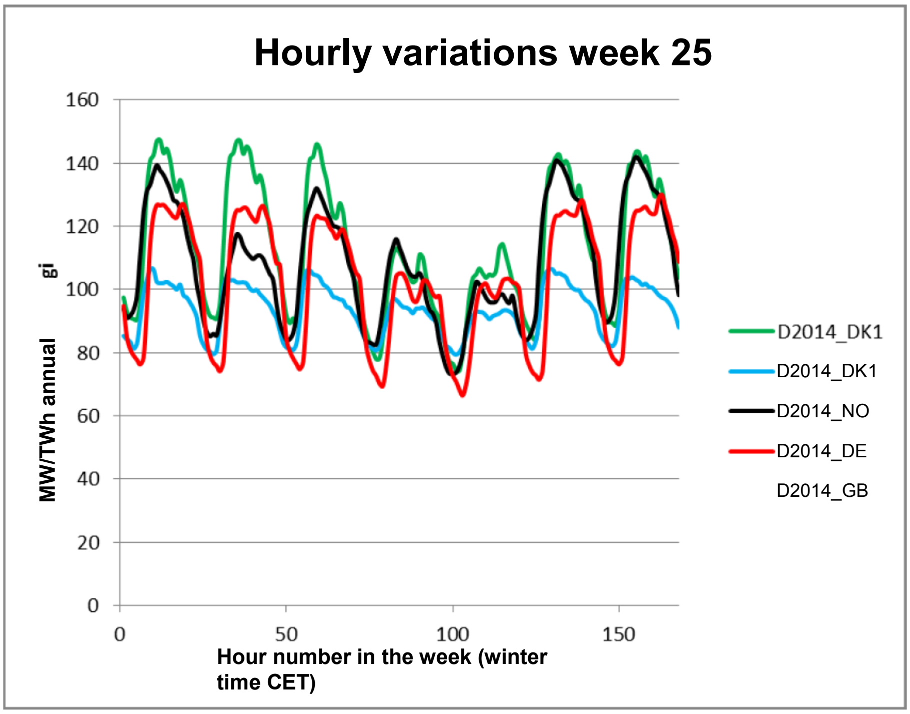

Figure 29 Variation in electricity demand week 25, 2014, in DK1, Norway, Germany and the United Kingdom.

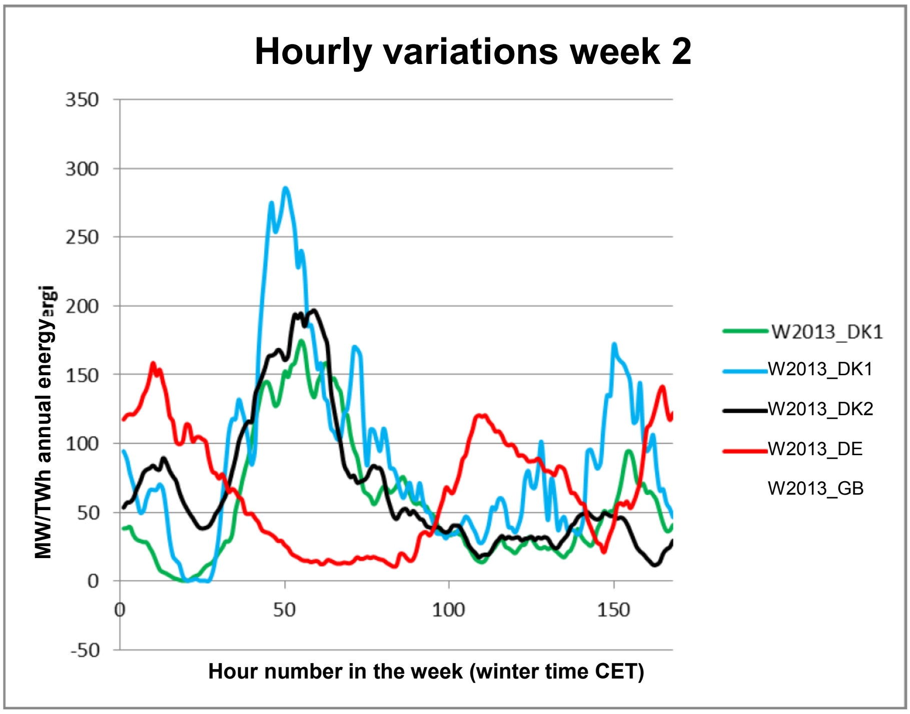

Figure 30 Variations in wind power generation week 2, 2013 in DK1, DK2 , Germany and the United Kingdom.

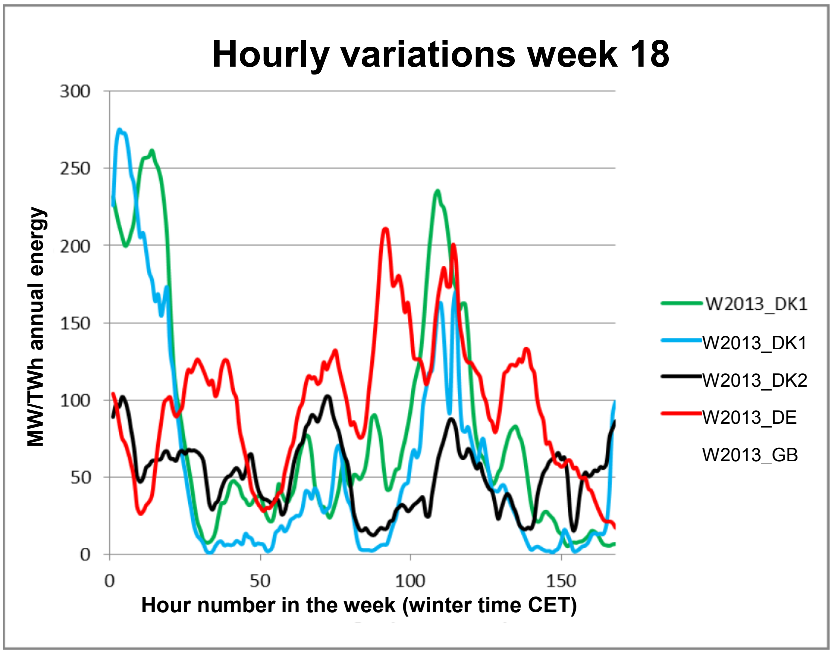

Figure 31 Variations in wind power generation week 2, 2013 in DK1, DK2 , Germany and the United Kingdom.

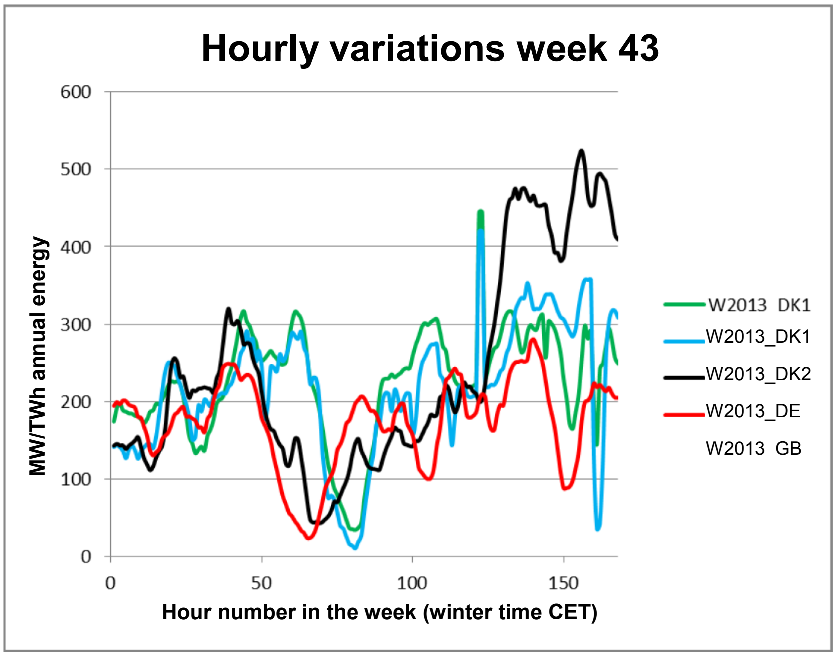

Figure 32 Variations in wind power generation week 43, 2013 in DK1, DK2 , Germany and the United Kingdom. Storm Allan struck in the period 27-28 October 2013 (starting at hour 121)

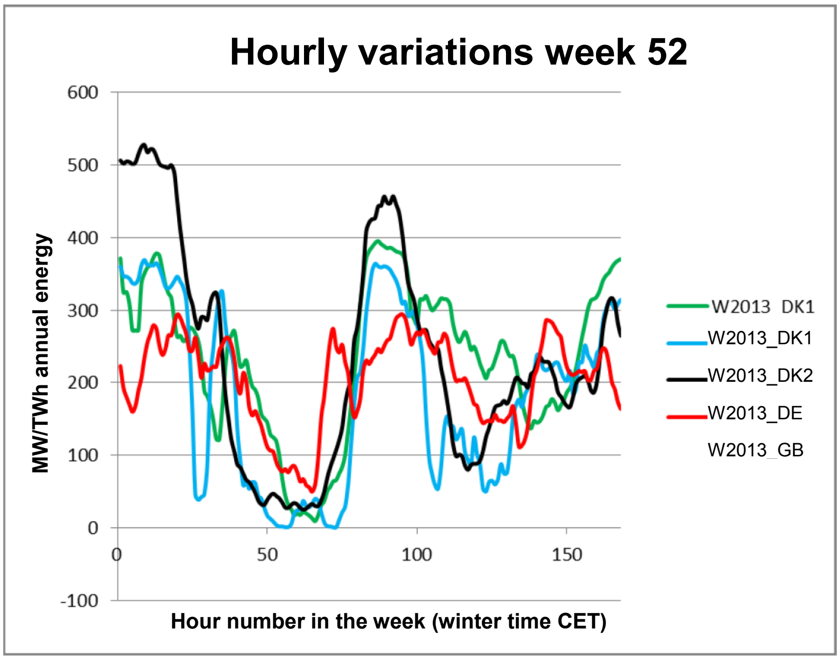

Figure 33 Variations in wind power generation week 52, 2013 in DK1, DK2 , Germany and the United Kingdom.

Annex C. Capacity balances and histograms

This Annex includes a number of capacity balances (figures 34-36) for countries included in the model calculation, either explicitly or as an external interconnector. It also includes a number of histograms that illustrate the probability distribution for the capacity available. Neither balances nor histograms can determine the capacity adequacy as such; however, they provide an indication of the capacity mix and import dependence.

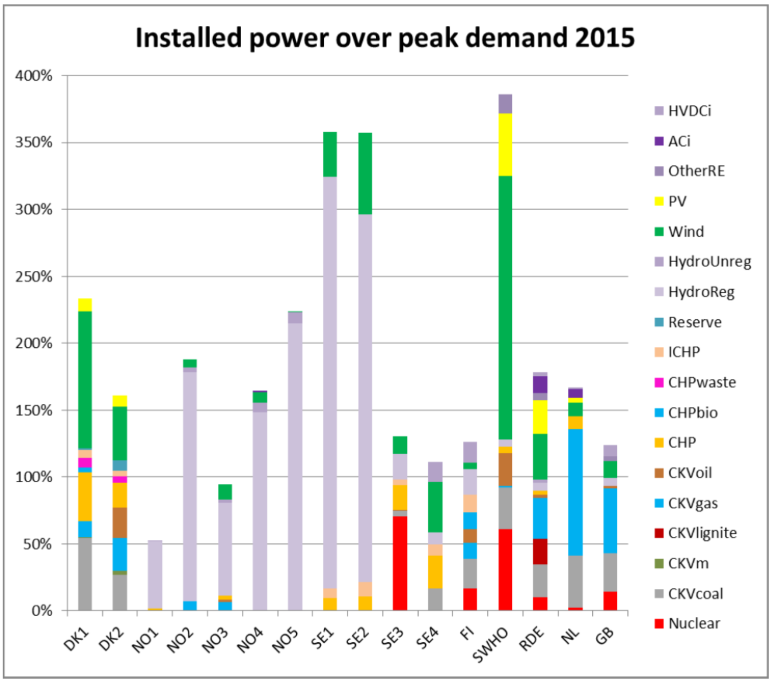

Figure 34 Installed capacity (percentage) in relation to annual peak demand 2015.

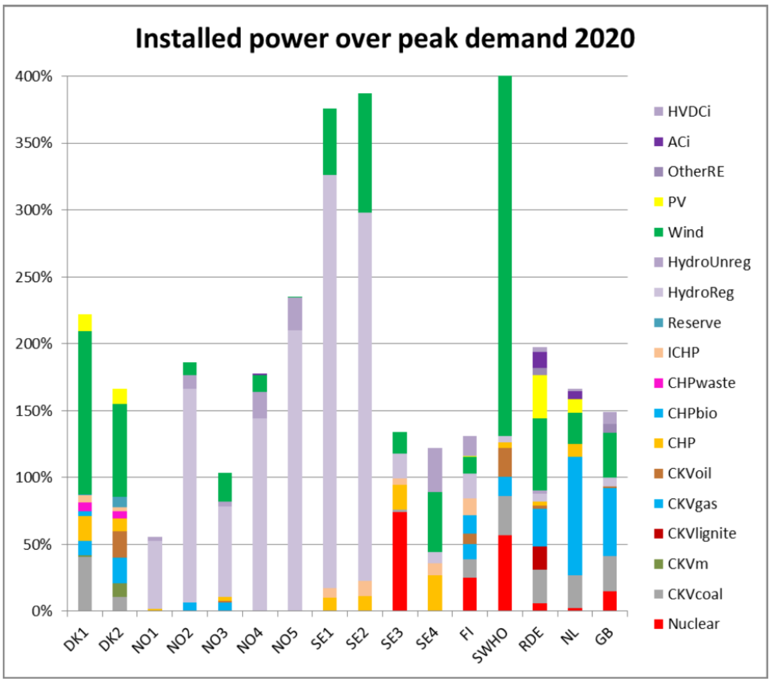

Figure 35 Installed capacity (percentage) in relation to annual peak demand 2020.

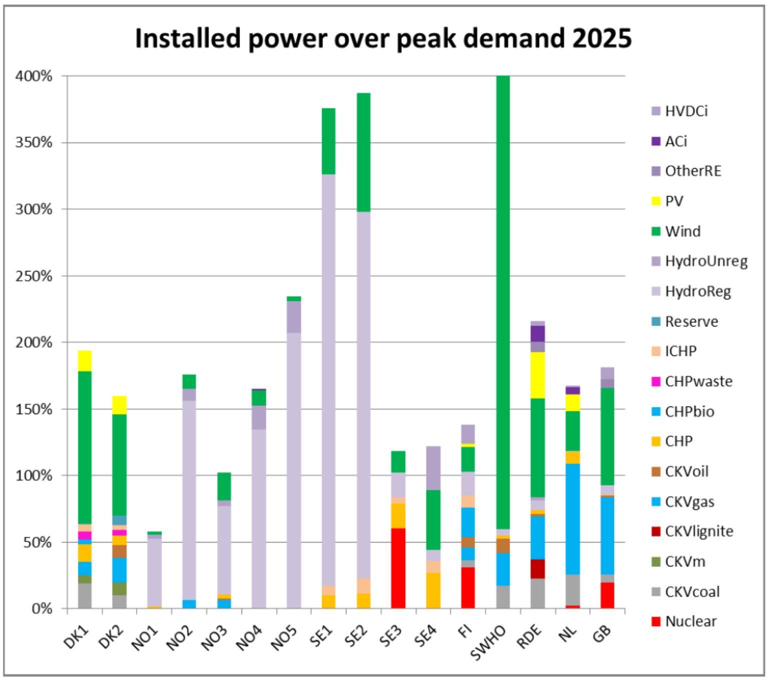

Figure 36 Installed capacity (percentage) in relation to annual peak demand 2025.

The following three figures (figures 37-39) show histograms of the capacity surplus in Denmark 2015, 2020 and 2025. The number of hours from the Monte Carlo simulations in which there was a capacity surplus or deficit with regard to demand at that given moment have been counted and analysed in a histogram, thereby providing a probability distribution (the area under each curve = 1). The curves for DK1 are flatter than for the other areas because there is relatively more wind in this area.

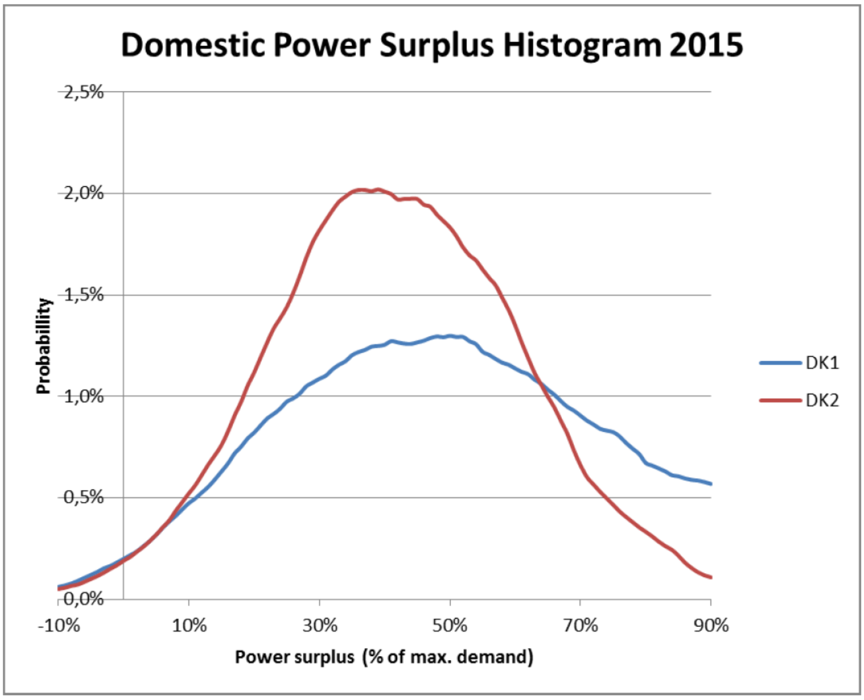

Figure 37 Histogram of capacity surplus in Denmark 2015.

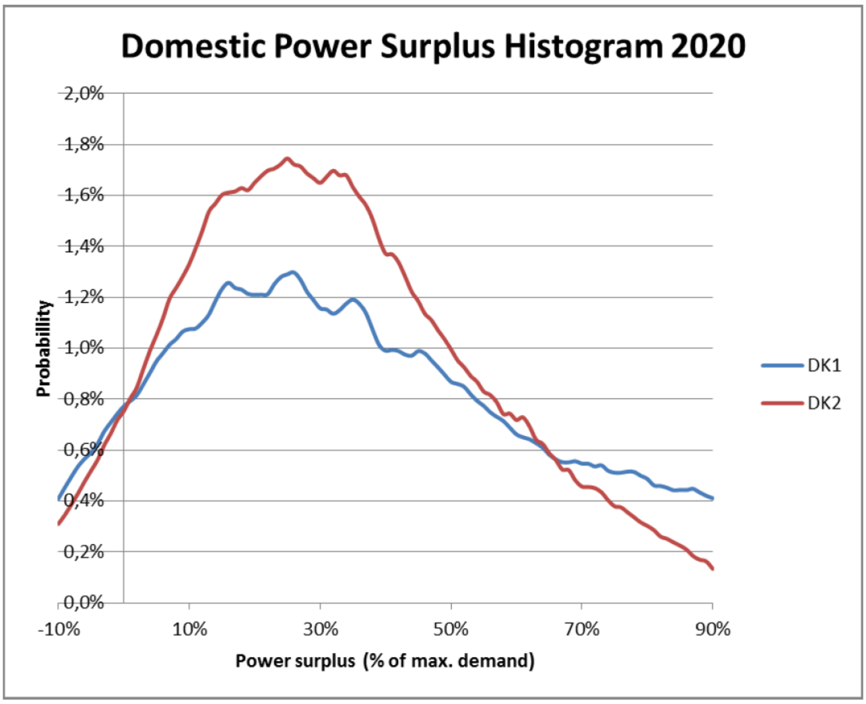

Figure 38 Histogram of capacity surplus in Denmark 2020.

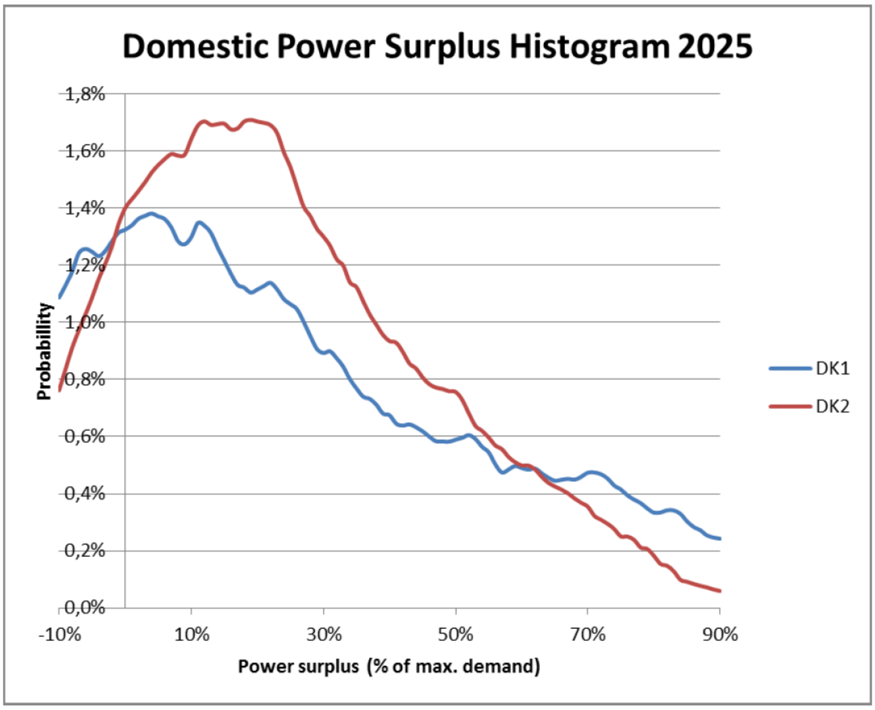

Figure 39 Histogram of capacity surplus in Denmark 2025.