Ea Energy Analyses

System adequacy in alternative wind power scenarios

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Content

Foreword

The NSON-DK project is the Danish part of a North Sea Offshore Network project. The project (under the EUDP program) studies how the future massive onshore and offshore wind power, and the associated offshore grid development in the North Sea, will affect the Danish power system in the short, medium and long term. The present report describes the results of work package 4 (WP4) of NSON-DK concerning the future system adequacy in the countries around the North Sea and with special focus on Denmark.

The evaluations of system adequacy are based on scenarios for the future power system towards 2050 in the countries around the North Sea. One of the scenarios includes an integrated North Sea offshore grid connecting offshore wind parks. The scenarios have been developed in WP2 of the NSON-DK project, where the Balmorel energy system model is used to carry out investment optimization for a project-based and an offshore grid scenario, respectively.

The project-based scenario follows the current trend of connecting the single onshore and offshore wind park individually to the transmission grid on land. The offshore grid scenario includes the option to build offshore wind hubs in the North Sea and connecting the hubs to form an offshore grid connected to the transmission grid on land. These scenarios are described in detail in (ref. 1 and 2).

The system adequacy calculations are carried out with the stochastic model SisyfosR, which includes both adequacy for transmission and generation, but not other security of supply aspects e.g. system security. For Denmark, the transmission system includes a full representation of the high voltage transmission system. For the remaining model area, the transmission system is limited to only include transmission lines connecting price areas. Countries can consist of one or more price areas. Transmission within price areas is considered to be unconstrained.

The report is organised as follows:

- Chapter 1 is an executive summary
- Chapter 2 describes data and assumptions for the system adequacy calculations
- Chapter 3 gives a brief description of the stochastic model SisyfosR
- Chapter 4 presents results and evaluations/discussions
- Chapter 5 is conclusions

1 Executive Summary

The NSON-DK project studies how the future massive onshore and offshore wind power, and the associated offshore grid development in the North Sea, will affect the Danish power system in the short, medium and long term. This report describes the results regarding the future system adequacy including generation and transmission. For Denmark, the transmission system includes the high voltage transmission system, while only interconnections between countries and model areas are modelled for the remaining model area comprising the countries around the North Sea.

The adequacy calculations are carried out with a stochastic model (SisyfosR). They are based on two future scenarios for the development of the power system towards 2050.

One scenario, the project-based scenario, follows the present trend of connecting the single onshore and offshore wind park individually to the transmission grid on land.

The other scenario, the offshore grid scenario, besides individually connecting wind farms to the transmission grid on land, includes an option for building offshore hubs in the North Sea. These are connected forming an offshore grid for integration of wind.

The scenarios have been developed in another work package of the NSON-DK project (work package 2), where the Balmorel energy system model is used to carry out investment optimization for transmission and generation.

This optimization results in massive development of wind and solar in all countries and a reduction of the sum of installed thermal generation in the system. In Denmark, however the thermal generation capacity grows from 5 to 8 GW toward 2050.

The most important results from the adequacy analyses on the transmission level can be summarised as follows:

- A massive wind power development onshore and offshore in the countries around the North Sea including Denmark will not compromise the system adequacy in Denmark.

- On average in Denmark adequacy numbers are improving from about 3.5 to 2.5 “power outage minutes” per year in both scenarios (project based and offshore grid) from 2020-50. The 3.5 minutes in 2020 are the result of calibration of the model with the currently observed consumer average outage minutes in the Danish system.
- Adequacy results are very similar in project-based and offshore grid solutions, as is the overall development of the generation portfolio of wind and PV, both on system level and in Denmark. The results show that the domestic transmission system in Denmark is pivotal for the “Energy Not Served”. The results with Eastern and Western Denmark simulated as interconnected copper plates (no constraints in transmission) show ten times fewer outage minutes in the project-based scenario in 2020 and for practical purposes zero in the other cases.
- The future regional capacity surplus is very pronounced in Denmark. Compared to the forecast from the Danish Energy Agency, the generation capacity in the scenarios are about 5 GW higher in 2030 in Denmark.
- The analysis fails to identify a correlation or causal relationship between the amount of wind and PV generation during events with lack of adequacy (on system level and in Denmark). In other words, in the scenarios investigated there is in general sufficiency of installed generation capacity of other technology (DK: thermal power) to secure the supply when generation from wind and PV is low.
- For Denmark in general, the events of adequacy deficit do not seem to be correlated with the available interconnector capacity feeding into the country.
- By contrast, the events of adequacy deficit (on system level and in Denmark) are to some extent correlated with the actual demand in a region: higher demand results in worse energy not served events.
- On system level, most adequacy deficit events occur when system generation capacity overall is abundant, but power cannot be transported to areas which have a deficit. Therefore, on system level in general, lack of available transmission capacity is the cause of “energy not served” situations.

2 Data and assumption

2.1 Model area – countries

The countries analysed in the adequacy model are taken directly from the work package 2 (WP2, ref. 1 and ref. 2), which describes the development of two future scenarios for the development of the power systems around the North Sea.

In WP2, the optimized development of generation and transmission assets is carried out for the primary countries around the North Sea: Denmark (DK), Norway (NO), Great Britain (GB), Netherlands (NL), Belgium (BE) and Germany (DE). In WP2 it was not deemed sufficient to focus solely on the mentioned North Sea countries, however, as electricity is traded across borders to their neighbours. Thus, secondary neig hbouring countries were also included in the energy system modelling: they take part in the energy market modelling but are not part of the investment optimization. Although, they do experience an assumed future energy system development as described by a specific exogenous scenario (see ref. 3).

Thus, the secondary countries included in the energy market modelling, in addition to the primary countries, are: Sweden, Finland, Estonia, Latvia and Lithuania (to include all of Nord Pool), and France and Poland.

The countries included in the adequacy modelling are the same as for the energy modelling (WP2) for similar reasons. Power flows are transmitted across boundaries between primary and secondary countries, which may have an impact on system adequacy.

2.2 Basis system data assumptions

The key starting points for developing the scenarios in WP2 are the 2020 generation portfolio in the countries and the assumptions regarding decommissioning of this portfolio over the years due to aging; the forecasts for demand for 2020-2050 and the assumed set of interconnectors between countries and subareas in the model in 2020. This has been reported in detail in WP2 (ref. 1, ref. 2 and ref. 3) and the main presumptions are briefly described in the subsections below, for convenience.

Basis generation assumptions

Figure 2.1 shows the generation capacities assumed to be installed in 2020 (GW). This figure is the exogenous boundary conditions for generation development in the investment optimization modelling in NSON-DK work package 2.

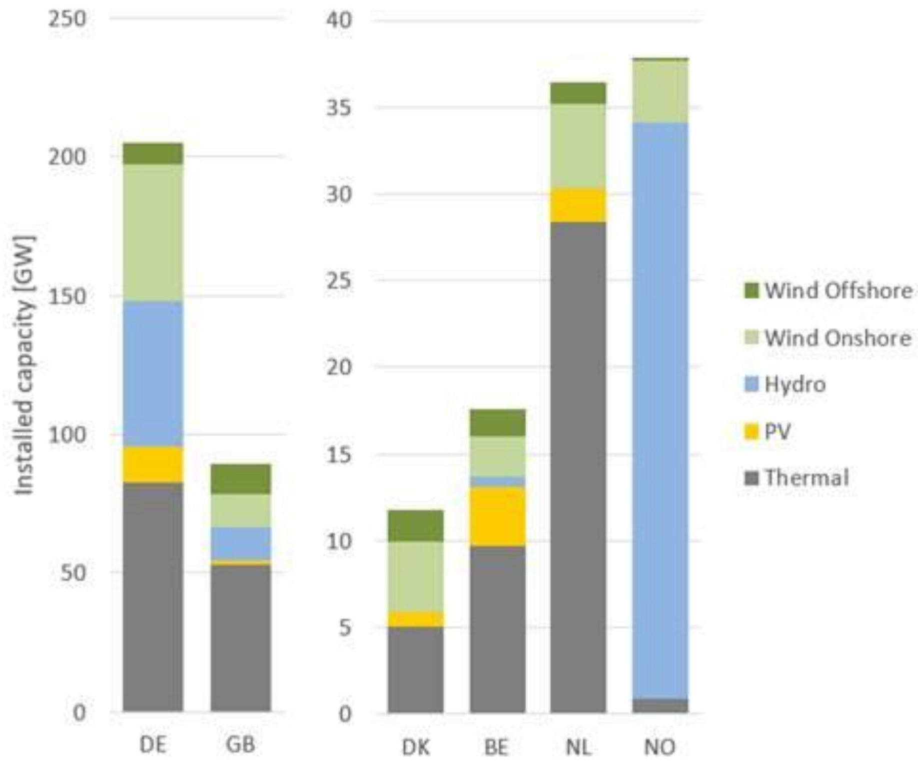


Figure 2.1. Generation capacities assumed to be installed in 2020 (GW), which is the starting point for the investment optimization modelling in NSON-DK.

Assumption for development of demand 2020-2050

The development of demand is a boundary condition (exogenous parameter) in the scenario formation in WP2. The assumed development for all countries is shown in figure 2.2.

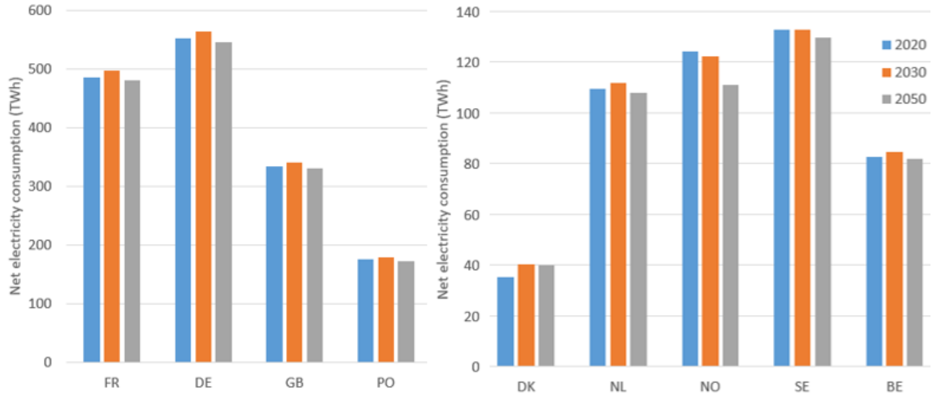


Figure 2.2 Assumed development of demand in countries in the total model area, comprising countries with optimization of generation and transmission (DK, NO, GB, NL, BE and DE) and some of the neighbouring countries.

Transmission/ interconnector capacities in basis year 2020

In accordance with figure 2.1 for generation, figure 2.3 shows the starting point for the optimization of the transmission system for connections between countries and price areas in the model. Except for Denmark, the domestic transmission grid inside the countries or subareas (price areas in Balmorel) are not taken into account. The assumption is that the power flow inside countries/price areas can occur without constraints (copper plates).

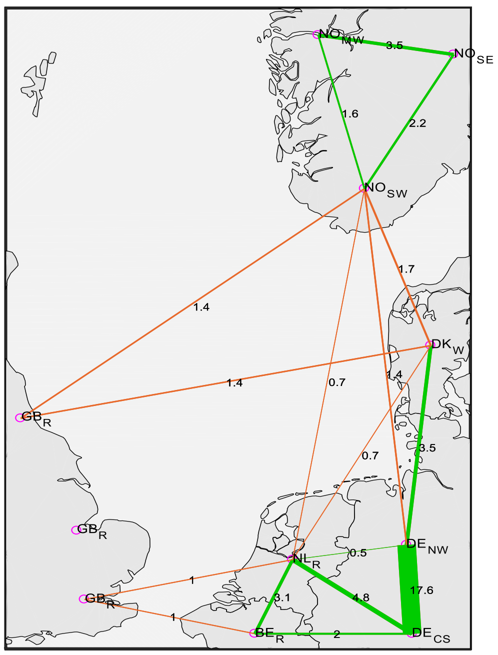


Figure 2.3. Assumed transmission system in 2020, which is the starting point for the Balmorel model optimization for 2030 and 2050. Capacities in GW. On-land lines are drawn in green and offshore lines in orange.

2.3 Assumptions for the Danish domestic transmission grid

Besides the above large-scale transmission system (fig. 2.3), the domestic transmission lines in Denmark have been included in the adequacy calculations for Denmark. The layout of the Danish domestic transmission system is shown in figure 2.4, which is the planned system for 2020. The transmission system comprises voltage levels above 100 kV, mainly consisting of 400 kV (red lines) and 150 kV/ 132 kV (black lines).

For the purpose of the analysis, the Danish domestic transmission grid is assumed to be unchanged in all calculations for 2020, 2030 and 2050 in both scenarios.

As is shown in section 2.4 the investments in Denmark in new wind and solar power are substantial towards 2050. The VRE generation capacity is growing from the starting point of about 7 GW in 2020 to 23-25 GW in 2050. This amount of new VRE will definitely call for additional domestic transmission lines or upgrading existing lines.

The assumption of a frozen Danish grid can be characterised as on the conservative side regarding adequacy results, meaning that future strengthening and extension of the grid will lead to improved transmission adequacy than in the case with the frozen 2020 grid capacities.

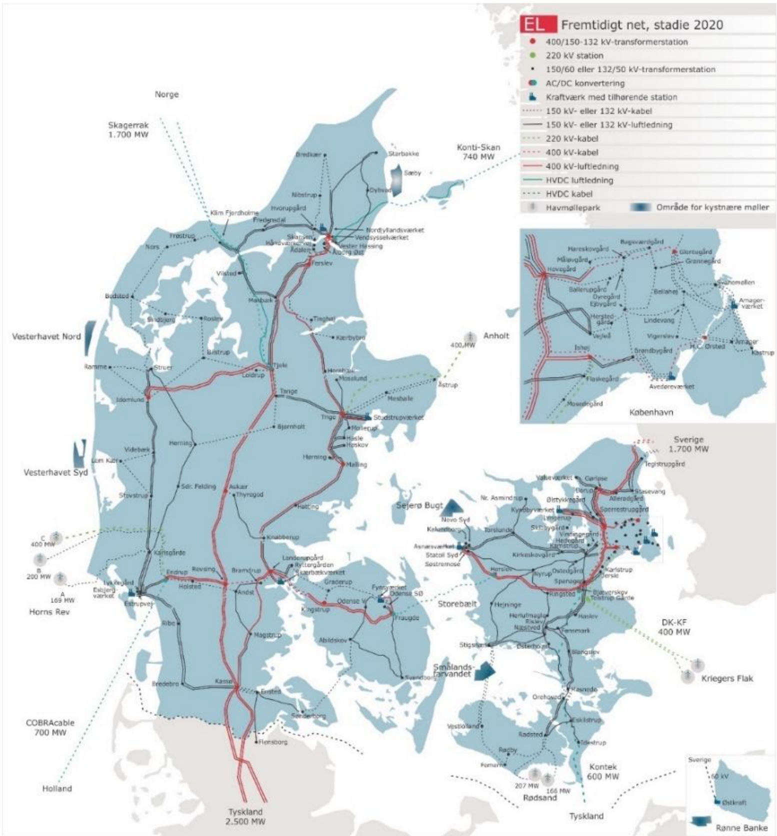


Fig. 2.4. Planned Danish domestic transmission system, 2020. Danish Energy Agency/Energinet.

2.4 Scenarios for 2030 and 2050

The optimized scenarios of generation and transmission from NSON-DK's work package 2 (ref. 1 and ref. 2) provide key input to the adequacy evaluations. The main results from the optimized scenarios are shown in the following figure 2.5 and 2.6 and in table 2.1 and 2.2. The results are reproduced directly from ref. 1 and ref. 2.

The optimization has been conducted with two sets of preconditions resulting in the project-based scenario and in the offshore grid scenario. The project-based scenario follows the present trend of connecting each onshore and offshore wind park individually to the transmission grid on land. In contrast, the offshore grid scenario also includes integration of offshore wind hubs in the North Sea to the transmission infrastructure of the region.

Project based scenario

Transmission grid results for 2030 and 2050 in the project-based scenario is shown in figure 2.5. It follows that the interconnectors have been reinforced both in 2030 and in 2050.

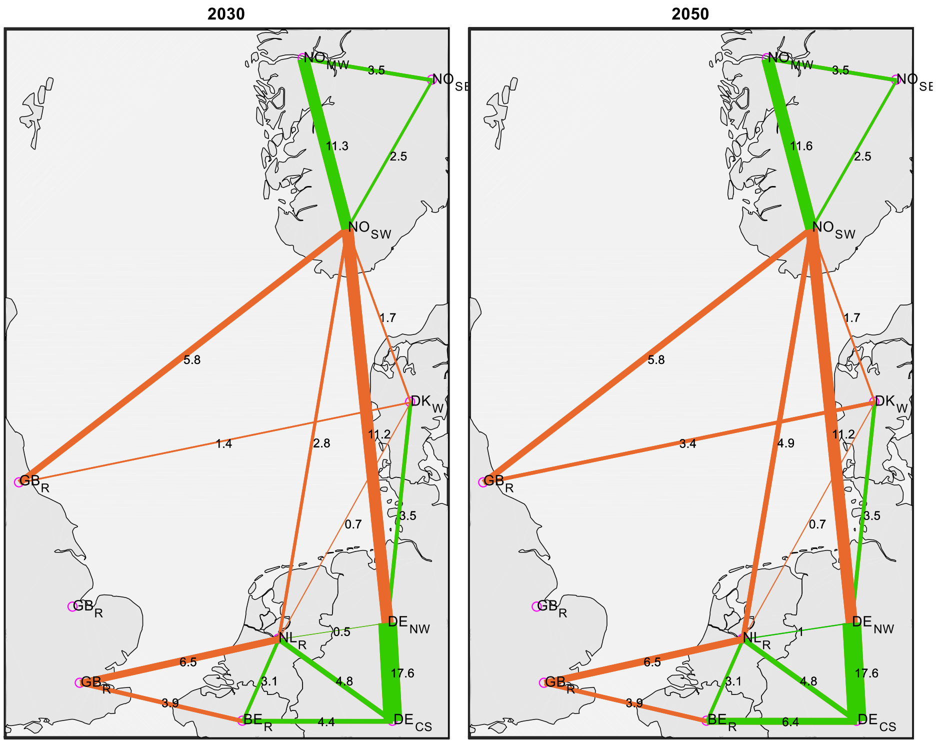


Figure 2.5. Project-based scenario: transmission lines in 2030 and 2050 [GW]. On-land lines in green and country-to-country offshore lines in orange.

Table 2.1 shows the generation capacities in the years toward 2050. For Denmark, the installed capacities of VRE increases from 6.7 GW to 23.6 GW towards 2050. It follows that the sum of thermal generation declines from 2020 toward 2050

It is noted that the capacity of thermal plants includes both CHP, condensing and reserve units, which means all available thermal generation for adequacy support is included.

Country	Solar			Hydro			Onshore wind			Offshore wind			Thermal		
	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050
BE	3,4	8,6	19,8	0,6	0,6	0,6	2,3	5,2	4,4	1,6	6,0	6,0	9,7	8,0	11,4
DE	52,0	84,3	103,7	13,4	13,4	18,2	49,5	59,0	64,0	7,4	7,8	16,2	82,7	75,6	66,2
DK	0,9	2,2	9,0	0,0	0,0	0,0	4,1	6,5	6,5	1,7	6,2	8,1	5,1	6,9	7,9
GB	11,5	17,9	37,2	2,0	2,0	2,0	11,9	28,1	20,0	10,5	30,2	33,8	53,1	42,2	41,9
NL	1,9	12,7	12,7	0,0	0,0	0,0	4,9	4,9	7,5	1,1	9,2	16,3	28,4	20,0	10,9
NO	0,0	0,0	0,0	33,2	33,2	35,1	3,5	15,9	11,4	0,0	4,0	11,5	1,0	1,0	1,0
Sum	69,8	125,7	182,4	49,2	49,2	55,9	76,2	119,6	113,9	22,2	63,5	91,9	179,9	153,7	139,2

Table 2.1: Project-based scenario: installed VRE, hydro and thermal generation capacities [GW] for optimized countries

Offshore grid scenario

Transmission grid results for 2030 and 2050 in the offshore grid scenario is shown in figure 2.6. When comparing with figure 2.3, it follows that the transmission grid /interconnectors have been reinforced both in 2030 and in 2050. The blue dots are offshore hubs to where offshore wind farms are connected. The size of the hubs (GW) are indicated in the figure. It follows that in 2030, for instance, 1 GW of wind is transmitted to the Danish grid from an offshore grid hub. The remaining Danish offshore wind (Table 3.2) is connected directly via radials to the Danish grid and is not shown in figure 3.7.

Table 2.2 shows the optimized generation capacities for the offshore grid scenario towards 2050. Numbers in bracket in Table 2.2 show the share of offshore wind being hub-connected.

For Denmark, the installed capacity of VRE increases from 6.7 GW to 24.4 GW. Overall, the results in Table 2.2 are very similar to the results for the project-based scenario in Table 2.1. The installed capacities of VRE (primary countries) increase from 168 GW to around 385 GW in both scenarios and the sum of thermal generation declines from 2020 toward 2050.

It follows from table 2.2 that only Germany, Norway and Denmark have hub connected offshore wind.

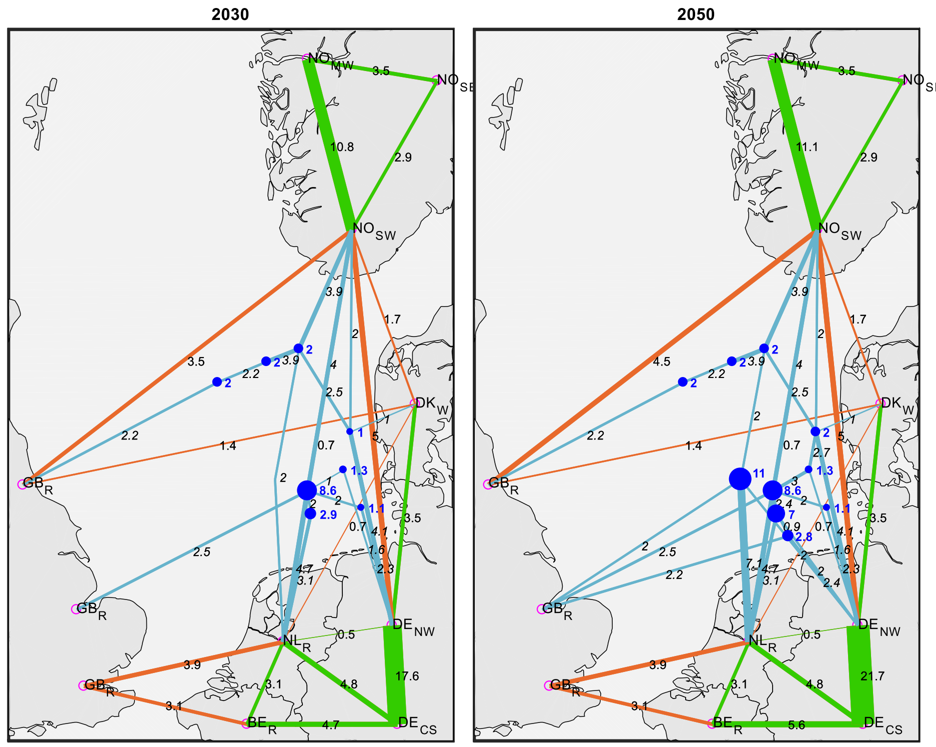


Figure 2.6. Integrated offshore grid scenario: transmission lines and hubs in 2030 and 2050 (GW). On-land lines in green, country-to-country offshore lines in orange, and lines related to the meshed grid in blue (hub size in dark blue).

Country	Solar			Hydro			Onshore wind			Offshore wind			Thermal		
	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050
BE	3,4	8,6	15,1	0,6	0,6	0,6	2,3	4,4	4,4	1,6 (0%)	6,0 (0%)	6,0 (0%)	9,7	9,1	11,0
DE	52,0	79,6	97,0	13,4	13,4	18,2	49,5	57,3	62,3	7,4 (0%)	21,3 (64%)	41,0 (77%)	82,7	73,9	65,1
DK	0,9	1,3	9,0	0,0	0,0	0,0	4,1	6,5	6,5	1,7 (0%)	7,0 (14 %)	8,9 (23 %)	5,1	6,9	7,9
GB	11,5	17,9	42,0	2,0	2,0	2,0	11,9	20,0	20,0	10,5 (0%)	27,7 (0%)	33,2 (0%)	53,1	42,3	40,0
NL	1,9	12,7	12,7	0,0	0,0	0,0	4,9	4,9	4,9	1,1 (0%)	1,1 (0%)	1,7 (0%)	28,4	16,5	9,6
NO	0,0	0,0	0,0	33,2	33,2	35,1	3,5	8,0	8,0	0,0 (0%)	6,2 (97%)	11,4 (52%)	1,0	1,0	1,0
Sum	69,8	120,1	175,9	49,2	49,2	55,9	76,2	101,1	106,1	22,2 (0%)	69,2 (30%)	102,2 (39%)	179,9	149,8	134,7

Table 2.2: Integrated offshore grid: installed VRE and fossil condensing capacities [GW] for the optimized countries

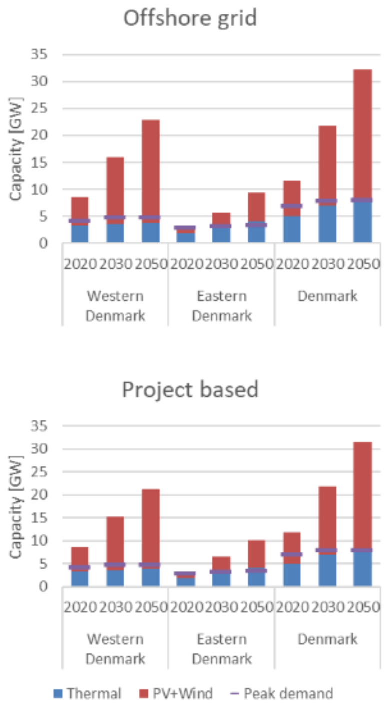
Generation capacities in Denmark in the two scenarios

Figure 2.7 shows the development of a generation portfolio for Denmark in the two scenarios.

The scenarios are compared with the official forecast from the Danish Energy Agency from 2018 (ref. 4). It follows that the overall trends show quite good resemblance in the two sets of results. However, as seen the generation numbers in (ref. 4) are somewhat smaller for both thermal capacity and for PV+wind than in the NSON scenarios. In 2030, NSON scenarios have about 15 GW of installed PV+wind and 7 GW installed thermal generation. The corresponding numbers from (ref. 4) are about 13 GW and 4 GW, respectively. Thus, compared to Danish Energy Agency forecasts, the generation capacity in the scenarios are about 5 GW higher in 2030 in Denmark.

From the day-ahead power market operation analysis in NSON WP3 (ref. 5) it follows that Denmark together with Norway are future net-exporters, while the remaining countries BE, DE, GB and NL are net-importers. In 2030 and 2050, Denmark's net export is estimated to be around 25-30 TWh/year in both scenarios.

Denmark, Numbers regarding 2030	Thermal [GW]	PV + Wind [GW]	Peak demand [GW]
Analysis Assumptions	4,34	12,72	8,47
NSON, Project based	6,91	14,86	7,71
NSON, Offshore grid	6,91	14,78	7,71



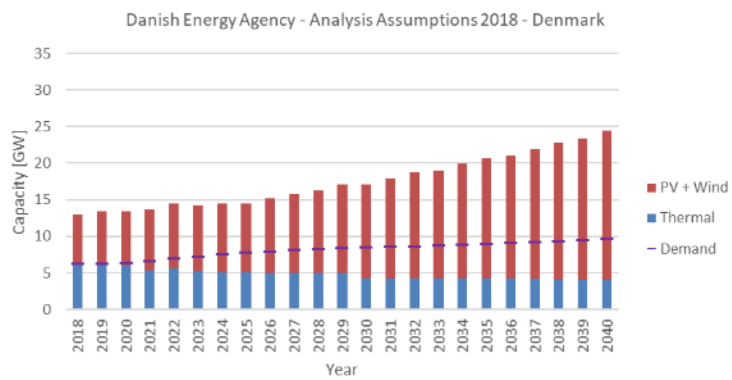


Figure 2.7. Generation portfolio in Denmark in the two scenarios together with forecast from Danish Energy Agency (ref. 4).

2.5 Specific presumptions for adequacy calculations

Generation

For power stations, each plant's capacity in a given hour is dependent on the probability for planned and unplanned outages. For wind and PV, outage numbers are not applied directly. Instead, generation profiles with hour by hour values through the year are implicitly assumed to take outages into account. For CHP units, max capacities have been adjusted over the seasons of the year taking into account delivery of heat.

Transmission

For transmission lines, the available capacity for a given hour depends on the assumed planned and unplanned outage probability.

For the domestic Danish transmission grid, it was necessary to do some adaptions. Some nodes in the 150 /132 kV grid are 'dead end' singletons and have only one connection to the remaining 150 kV/132 kV grid. The single nodes proved to be a problem, because they caused unreasonably high outage minutes, which biased the aggregated results for Denmark.

In reality, the 150/132 kV nodes do not end blindly, but are connected to the medium level 25-99 kV distribution system via substations and can be fed from there in case the single connecting line in the transmission grid fails. To model this in a reasonable way, a synthetic additional "redundant" grid representing the underlying voltage levels was added to the physical 150/132 kV transmission grid. Then a common availability for the "redundant" grid was used as calibration factor, such that the estimated Danish outage minutes for demand in the model calculations complied with the statistics for outage minutes in the Danish grid for voltage level above 25 kV. From (ref. 6), the last 10 years' average values (2008-17) for Denmark were in intervals of 1-5 minutes for outages in systems above 25 kV. The final calibration result ended on a value of about three outage minutes for aggregated Denmark (see figure 5.3) in 2020 in the project-based scenario.

Demand time series

Each node in the adequacy model has an annual demand and an hourly variation profile, resulting in an hourly time series for demand.

3 Adequacy model – SisyfosR

3.1 The SisyfosR model

The Danish Energy Agency developed the original Sisyfos tool for analysing the security of electricity supply in power systems. Sisyfos simulates a high number of scenarios for the power generation capacity (power plants, wind, PV etc.) and transmission network capacity to assess the risk of power shortages. In cooperation with the Danish Energy Agency, Ea Energy Analyses has developed a new version, called SisyfosR, which performs about 100 times faster than the original model, and therefore allows for more precise simulation results.

The starting point is that power plants and transmission connections have a certain risk of outage. The model is stochastic and calculates the probability of situations where not all electricity demand can be served. This is performed by Monte Carlo simulations. The probability of outage of power plants as well as transmission lines is used to calculate ENS (Energy Not Served) by running a high number of random cases. Thereby, even rare situations can be described.

SisyfosR delivers the results with no regards to economics or optimal dispatch. It is a stochastic analysis, and it is a powerful model for calculating adequacy of power systems.

The SisyfosR model has been used to assess power supply security in Lithuania, South Africa and Denmark.

The main principles of SisyfosR is described in fact boxes 1 and 2 in figure 3.1 and figure 3.2.

SisyfosR

SisyfosR is a simulation model for investigation and evaluation of power system adequacy.

The model is suitable for analyses of long-term system adequacy in bulk power systems (generation and transmission), including power system changes induced by:

- Increasing renewable penetration
- Decomissioning of thermal power plants
- Introduction of new technologies

This enables location of weak points in the power system due to insufficient transmission or production capacity.

SisyfosR performs a Monte Carlo simulation evaluating a year of operation based on a number of different runs. The runs will all investigate the same year, but with varying outage occurances on power plants and transmission lines.

Key inputs

Generation

- Capacity (MW), planned and unplanned outages (%)
- Profiles for variable generation

Grid

- Line capacities, connections and outages

Demand

- Annual consumption and demand profile

Results

Expected Energy Not Supplied (EENS) [MWh]

- Expected annual unserved energy demand (due to insufficient supply or grid capacity)

Loss of Load Probability (LoLP) [%]

- The probability of ENS occurring

Figure 3.1. SisyfosR – Fact box 1

Problem formulation

System adequacy is determined by whether there is sufficient available power and grid capacity to supply the demand. The grid is taken into consideration, meaning demand can only be supplied if there is available capacity to route the supply through the grid.

This is for SisyfosR implemented by maximizing the flow of energy between nodes using the mathematical formulation illustrated below.

Terminology

The power system is defined by a set of nodes. Each node i can have a demand D_i and an available power capacity P_i. The available transmission capacity between two nodes i and j of the network is denoted C_{ij}, where F_{ij} then indicates the transmission between said nodes.
The nodes are then divided into two groups:
nodes with surplus capacity $\{i \in S | P_i - D_i \geq 0\}$
and
nodes with surplus demand $\{i \in T | D_i - P_i > 0\}$.

Energy Not Supplied can be calculated as such:

$$ENS = \sum_{i \in T} (D_i - P_i - \sum_j F_{ji})$$

Mathematical formulation

Max $\quad \sum_j \sum_i F_{ij}$

Where $\quad \sum_j F_{ji} \leq D_i - P_i \; \forall i \in T$

Inflow less than surplus demand

$-C_{ji} \leq F_{ij} \leq C_{ij}$

Flow within capacity limits

$\sum_j F_{ij} \leq P_i - D_i \; \forall i \in S$

Outflow less than surplus capacity

Visual interpretation

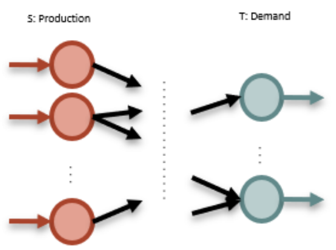


Figure 3.2. SisyforR – Fact box 2

4 Adequacy results and discussion

4.1 The model results in general

In the following the “modelled system” or “system” means the total system comprising both the primary countries: Denmark (DK), Norway (NO), Great Britain (GB), Netherlands (NL), Belgium (BE) and Germany (DE) and the secondary “non-optimized” countries (see section 2.1). The secondary countries are Sweden, Finland, Estonia, Latvia and Lithuania (to include all of Nord Pool), and France and Poland.

Number of model- runs in the Monte Carlo simulations

Figure 4.1 and 4.2 show the calculated expected energy not served (EENS) in eastern and western Denmark and in total for Denmark for 2050 in both scenarios: “project based” and “offshore grid”. It follows that the uncertainty expressed by two times the standard deviation (2SD) on the expected value decreases with increasing number of simulated years, each new run of the year with a different set of values for the stochastic variables in the model. Based on these results, it was decided to conduct the succeeding model calculations with 250 runs per year as standard, corresponding to a sampling of 2.19 million hourly situations. With 250 runs, it was judged that the uncertainty on the mean values of model results were limited compared to other inherent uncertainties stemming from imperfect data (generation, transmission, demand) and model setup simplifications.

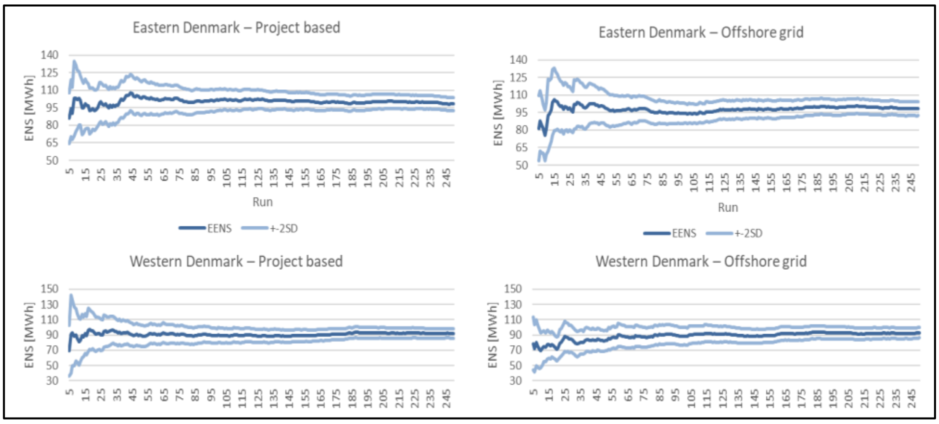


Figure 4.1 Expected energy not served (EENS) in 2050 scenarios “project based” and “offshore grid” for Eastern and Western Denmark on transmission level. 250 runs were performed.

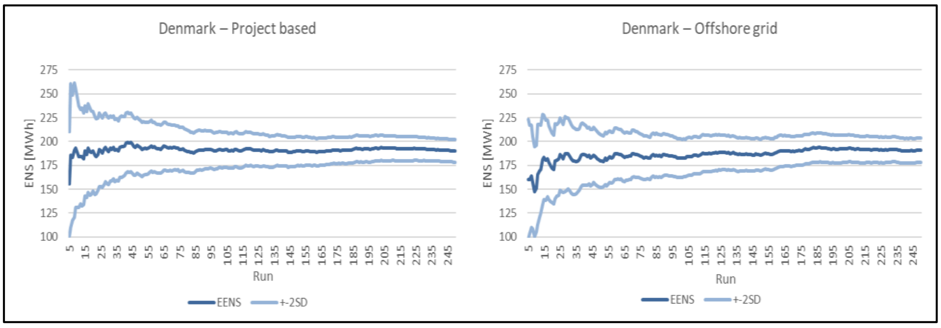


Figure 4.2 Expected energy not served (EENS) in 2050 scenarios “project based” and “offshore grid” for Denmark on transmission level. 250 runs were performed.

4.2 Key results on adequacy for Denmark

System adequacy – key numbers

As described in section 2.5, the Danish transmission system with voltages above 100 kV has been modelled. In this process, it was necessary to calibrate the model to give reasonable results. The calibration was carried out for a 2020 project-based scenario to give outage minutes in accordance with present outage statistics published in (ref. 6), see section below.

Key results on the system adequacy for Denmark are depicted in figure 4.3. It follows that the expected outage minutes (or so-called “power minutes”) for an average consumer are very low for all years and very similar for the two scenarios. The results show decreasing numbers from about 3.5 minutes to 2.5 minutes in both scenarios from 2020 to 2050, with numbers in Eastern Denmark relatively higher than in Western Denmark. Other studies show the same tendency, with outage minutes being higher in Eastern than Western Denmark (ref. 7).

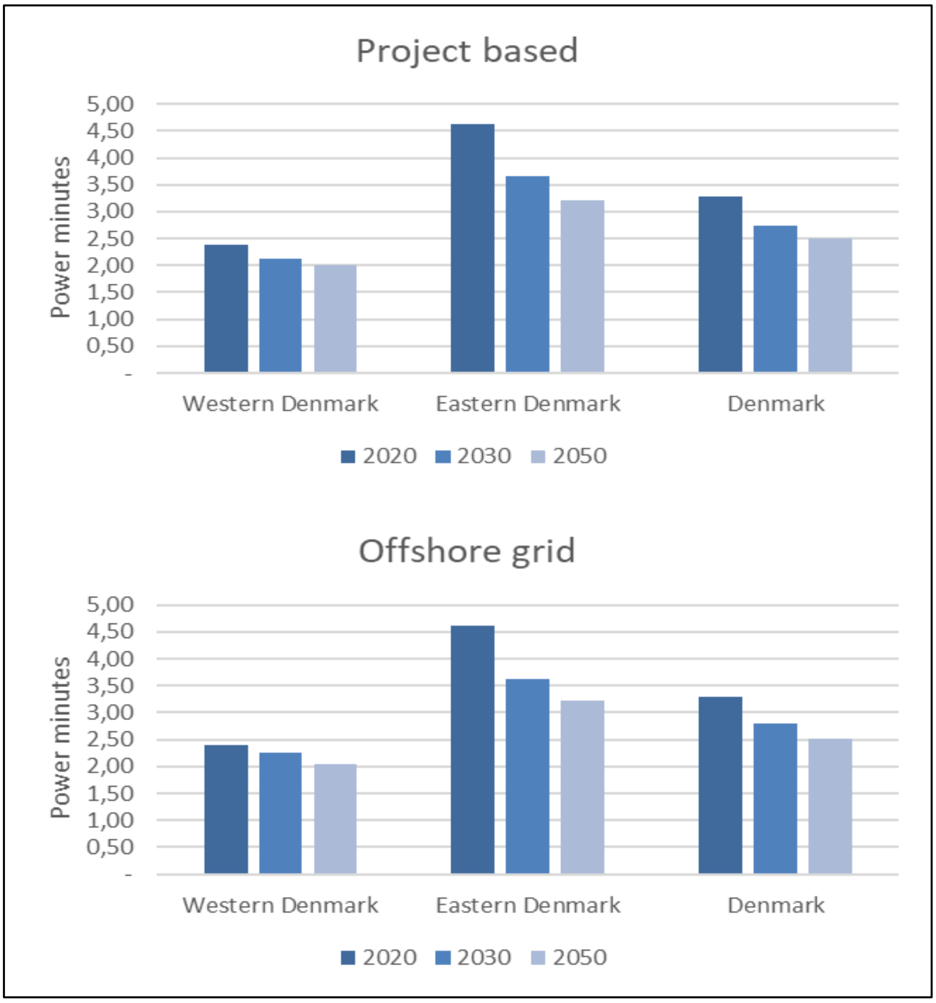


Figure 4.3. Key results for system adequacy on transmission level in Denmark, 2020-2050, when considering generation and transmission grid. Expected outage minutes (power minutes) for the average consumer.

The importance of the internal transmission grid in Denmark

The impact of considering the internal Danish transmission grid for estimation of outage minutes has been studied. Figure 4.4 shows the results when both of regions Denmark-west and Denmark-east have been assumed to be electrical copperplates with no internal transmission constraints. It follows that the outage minutes or "power minutes" (minutes without power supply for an average consumer) in "project based" has dropped with a factor of about 20 in 2020 in Eastern Denmark. In Western Denmark the number of outages is even smaller and practically zero in 2020.

For 2030 and 2050 and for all scenarios in "offshore grid" the calculated power minutes are also zero (for practical applications).

It follows from these results that including the internal transmission grid in Denmark in the model is of pivotal importance for the system adequacy results. The generation adequacy is not a problem. In the two scenarios, Denmark has substantial amounts of wind plus PV installed in the future: from about 7 GW of wind + PV in 2020 to about 25 GW in 2050 with modest increase in peak demand from about 6 GW to 8 GW in the same period (table 2.1, 2.2 and fig. 2.7).

From this can be concluded that the decline in "power minutes" in figure 4.3 from 2020 to 2050 is caused by increased "local generation", which does not need transmission for providing adequacy.

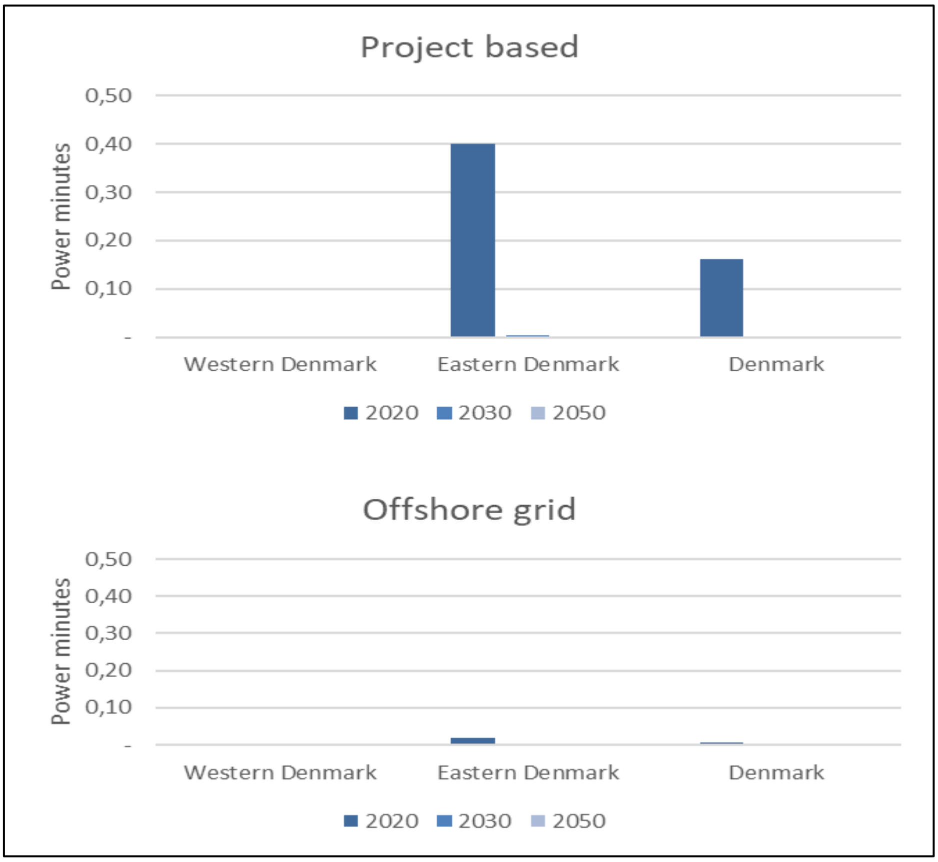


Figure 4.4. Results without considering the domestic Danish transmission grid. Eastern and Western Denmark are modelled as copper plates. Results for system adequacy on transmission level in Denmark, 2020-2050. Expected outage minutes (power minutes) for average consumer.

4.3 Generation capacity surplus – system-wide and for Denmark

Figure 4.5 shows cumulative probability distributions of capacity surpluses in the two scenarios ("project based" and "offshore grid") for 2020, 2030 and 2050. The capacity surplus is defined as how much the available generation capacity in a given point in time is larger than the demand (in percent); e.g. 0 percent indicates that the available capacity equals the demand. All capacity surplus above 100% are not depicted in the figure despite being present.
The available generation capacity is never below zero and it follows that the surplus of generation increases over the years. For the "offshore grid" this applies for both time periods 2020-2030 and 2030-2050. For "project based" the development stops at 2030, which in practical terms has the same surplus as 2050.

The results show a high degree of abundance of generation capacity (primarily wind and PV, see table 2.1 and 2.2). In 2050 there is only about 20 % probability that generation surplus is below 50% in both "project based" and "offshore grid", respectively.

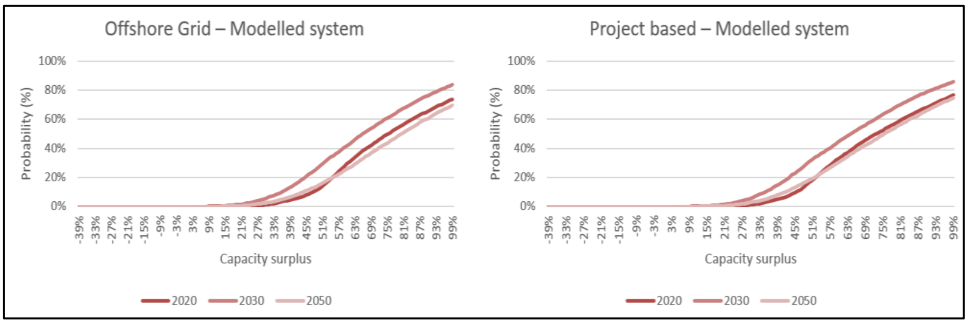


Figure 4.5. Cumulative probability distribution of capacity surplus 2020, 2030 and 2050 in "offshore grid" and "project based" scenarios for the system (optimized countries).

The corresponding results for Denmark are depicted in figure 4.6. The cumulative probability distribution functions for 2020 do show negative values for both Eastern and Western Denmark, especially for 2020. Compared to 2020, the generation capacity surpluses become very large in 2030 and 2050 in both scenarios and for both regions.

The distribution functions are flatter than for the system (fig. 4.5). This should be expected, as the Danish wind resource area is much smaller with aggregated wind generation more variable than for the whole system. For 2050, the figure shows that negative values do occur, but seldomly. On the other hand, abundant generation surplus is also occurring more due to the same reason.
In 2050, the generation surplus is above 99% in 80 to 90 percent of the time.

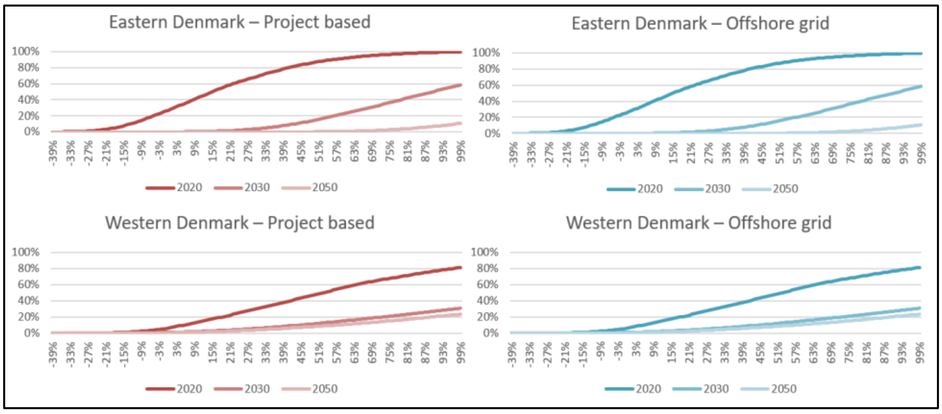


Figure 4.6 Cumulative probability distribution of capacity surplus 2020, 2030 and 2050 in “off-shore grid” and “project based” scenarios.

The results for Denmark compared to the overall system are in accordance with the VRE investments in Denmark being relatively higher than on average in the system (table 2.1 and table 2.2). Denmark and the North Sea area become a large net exporter area of renewable energy to the remaining Europe.

4.4 System generation capacity surplus and ENS

The model results in figure 4.7 illustrate the correlation between occurrence of hours with a specific generation surplus (red line) and hours (blue line) with ENS (Energy not served) on system basis. The figure is for 2020 and 2050 for offshore grid and project-based scenarios.

The results show a correlation between the two curves (red and blue), most obvious for 2050. Generation surplus values with a high occurring number of hours also have high numbers of hours with ENS and vice versa.

For 2050, the red curves are more uniformly distributed compared to the 2020 red curves, which is the result of massive VRE investments causing more hours with higher generation surplus.

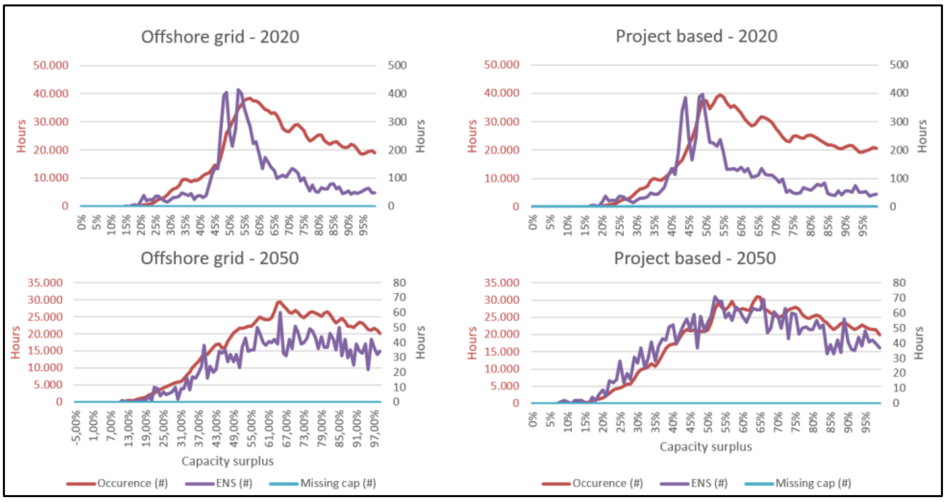


Figure 4.7. Correlation between occurrence of system generation surplus (percentage surplus above demand) and situations with energy not served.

It can be observed from figure 4.7 that the capacity surplus on system basis is positive in all cases. This means that the occurrences of ENS situations are due to lack of transmission resources between countries and internally in the Danish domestic transmission grid as discussed in section 4.2. Power from surplus areas in the model cannot be transmitted to deficit areas, causing energy not served situations.

4.5 Occurrence of energy not served in Denmark

Figures 4.8 and 4.9 show histograms of energy not served, distributed on years out of a total of 250 years of Monte Carlo simulations. The figures show results for Eastern and Western Denmark (figure 4.8) and aggregated for Denmark (figure 5.9). The histograms can be interpreted as realisations of the probability density functions for energy not served. The results are for 2050 for both the "project based" and "offshore grid" scenarios.

It follows that the histograms tend to be bell-shaped with a skewness towards the right. This is expected because the distribution has a well-defined lower boundary of zero, while the function can attain very high values. As expected, this feature is most dominant in figure 4.8, as the regions are "smaller areas". The results show years with ENS values more than two times the average values. As an example, the average value of ENS for Denmark (figure 4.9) is about 180 MWh/year, while the highest values are about 400 MWh/year (offshore grid scenario).

It can be verified that the average value of 180 MWh corresponds to about 2.5 outage minutes (power minutes), which accords with the results in figure 4.3.

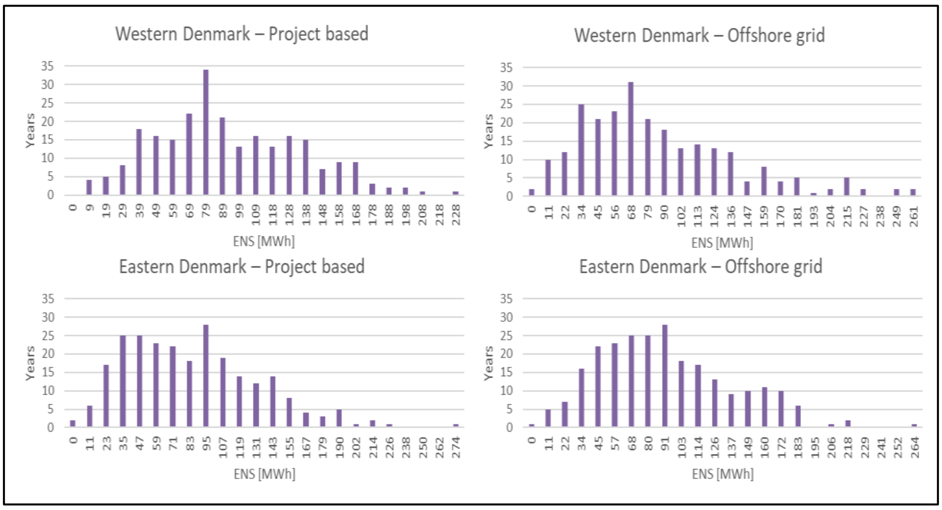


Figure 4.8. Distribution of energy not served (MWh) on number of years (total of 250 years) in Eastern and Western Denmark.

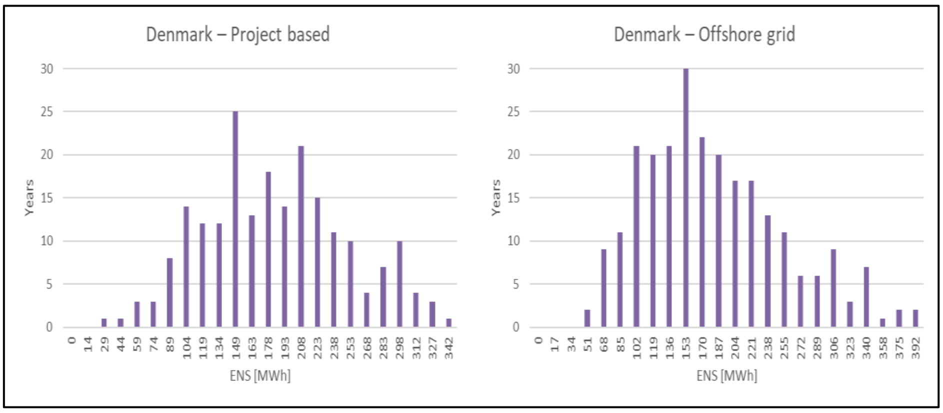


Figure 4.9 Distribution of energy not served on number of years (total of 250 years). Aggregated for Denmark.

4.6 Impact of selected factors for the future system adequacy

Impact of wind plus PV in the modelled system and in Denmark

Figure 4.10 depicts the sorted, calculated PV + wind generation for the system and its relation to the share of EENS (Expected Energy not served) in 2050 for both scenarios (“project based” and “offshore grid”). Summing the columns in the figure sums to 100 percent. The figure is the result of 250 years of Monte-Carlo simulations.

One might expect ENS to be higher with lower PV+wind. However, that is not the case. The histogram values are quite evenly distributed over the hours of the year. The explanation for this is that at there is available thermal and/or hydro capacity in 2050 when the PV+wind generation is not able to cover the demand (see table 2.1 and table 2.2). Besides, for higher values of PV+wind the ENS events do not seem to be directly linked to the amount of VRE generation.

Figure 4.11 shows the corresponding results for Eastern and Western Denmark. For Denmark, the results look similar to the system-wide results with a very even distribution of ENS over the hours, without a visible correlation to the PV+wind generation capacity. When the available PV+wind generation is low in Denmark and not able to cover the demand, then power import from abroad and/or domestic thermal capacity is available to cover the Danish demand to the same degree as when PV+wind is available. Besides, for higher values of PV+wind the ENS events do not seem to be directly linked to the amount of VRE generation.

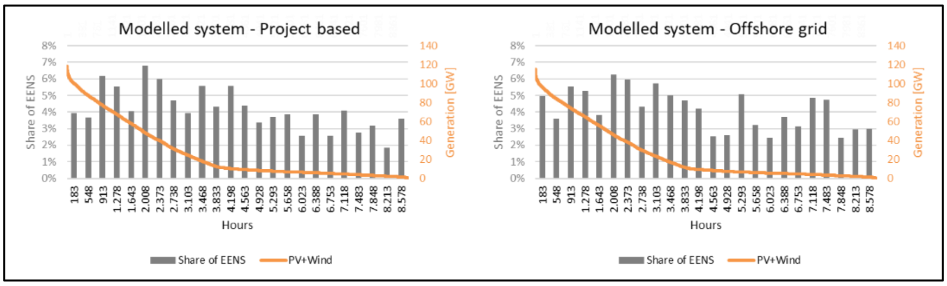


Figure 4.10 Impact on ENS (Energy not served) of VRE generation capacity, System 2050

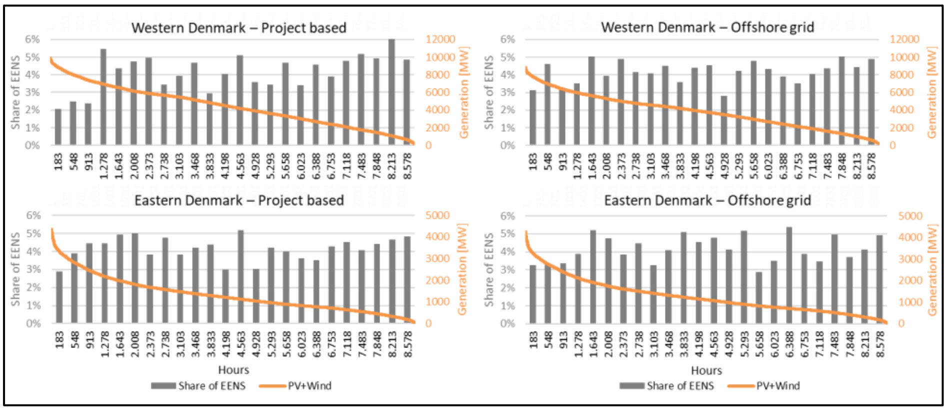


Figure 4.11 Impact on ENS (Energy not served) of VRE generation capacity, Eastern and Western Denmark 2050

Impact of demand in the modelled system and in Denmark

Figure 4.12 and figure 4.13 are analogue to figures 4.10 and 4.11, now with demand replacing PV+wind generation. In contrast to PV+wind, the size of demand has a correlation with the share of EENS (expected energy not served) in all cases. The correlation is as expected: the share of EENS declines with declining demand. This correlation seems particularly clear for the “system” in the “project based” scenario.

It should be noted that the scale on the second axis differ in the two figures.

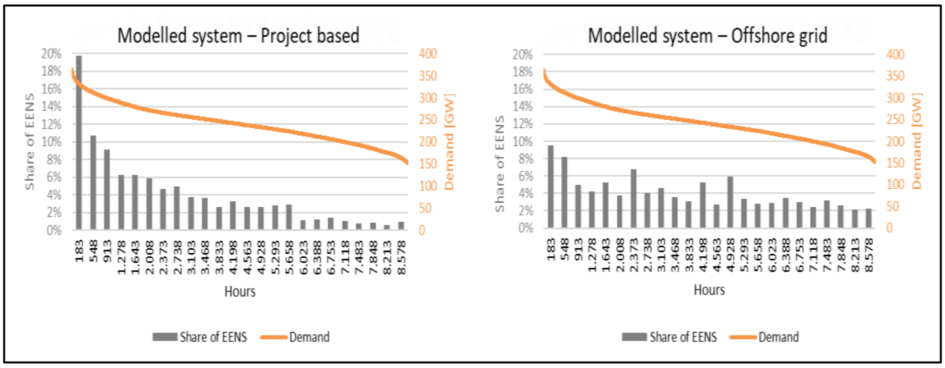


Figure 4.12 The impact of demand on ENS (Energy Not Served), total system, 2050

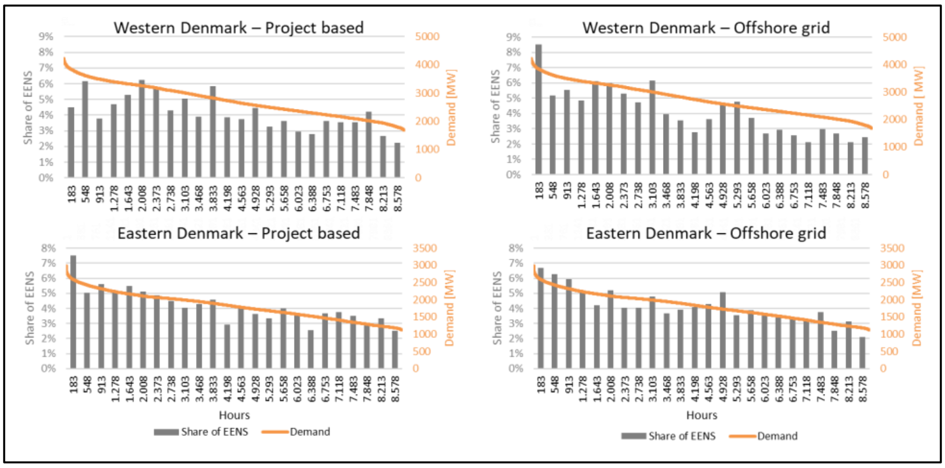


Figure 4.13 The impact of demand on ENS (Energy Not Served), Eastern and Western Denmark, 2050

Impact of available transmission capacity into Denmark

The model results concerning correlation between EENS in Denmark and available transmission capacity from abroad are depicted in figure 4.14. The results are shown for Eastern and Western Denmark for both scenarios ("project based" and "offshore grid") in 2050.

In all cases, there seem to be no correlation between share of EENS and available transmission capacity into the major Danish regions (Eastern and Western Denmark). The distribution of EENS is fairly uniform in all four graphs and therefore ENS for practical purposes is deemed independent of transmission capacity feeding into the regions.

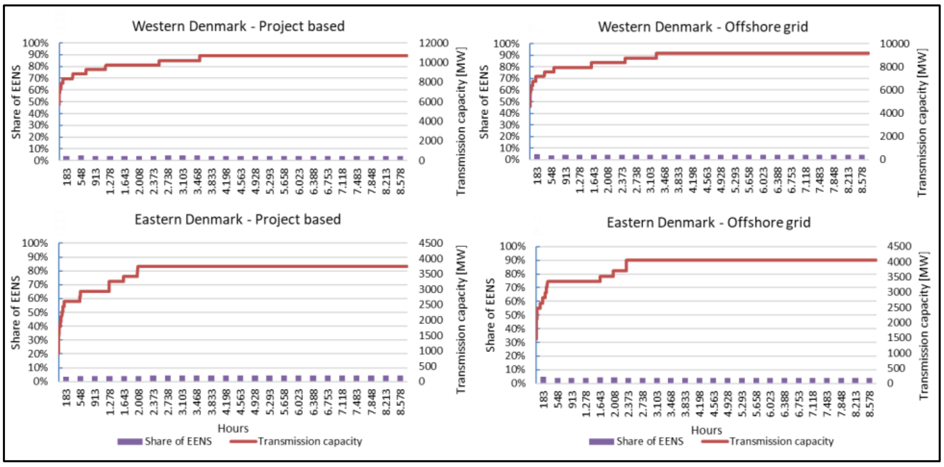


Figure 4.14 Impact on ENS (Energy not served) in Denmark of available transmission capacity into Denmark from abroad

5 Conclusions

The adequacy calculations have been carried out with a stochastic model (SisyfosR) and are based on two future scenarios for the development of the power system towards 2050. One scenario, the project-based scenario, follows the present trend of connecting the single onshore and offshore wind parks individually to the transmission grid on land. The other scenario, the offshore grid scenario, besides individually connected wind farms to transmission grid on land, includes an option for building offshore hubs in the North Sea and connecting the hubs forming an offshore grid for integration of wind.
In both future scenarios, the development of wind and PV in the studied countries around the North Sea is substantial, while the thermal plant portfolio on system level is declining. In Denmark, however the thermal capacity grows from 5 to 8 GW toward 2050.

For Denmark, the installed PV capacity grows from 900 MW in 2020 to 9.0 GW in 2050 in both scenarios. The development of installed wind capacity is quite similar in Denmark in the two scenarios. In the project-based scenario, onshore wind increases from 4.1 to 6.5 GW, while offshore wind grows from 1.7 to 8.1 GW from 2020 to 2050. The corresponding results for the offshore-grid scenario are 4.1 to 6.5 GW for onshore wind and 1.7 to 8.9 GW for offshore wind, respectively. Of the 8.9 GW, 23% is hub-connected.

The adequacy calculations indicate a downward trend in outage minutes towards 2050 for both Eastern and Western Denmark in both scenarios.
The most important results from the adequacy analyses on the transmission level can be summarised as follows:

- A massive wind power development onshore and offshore in the countries around the North Sea including Denmark will not compromise the system adequacy in Denmark.
- On average in Denmark, adequacy numbers are improving from about 3.5 to 2.5 power outage minutes per year in both scenarios (project based and offshore grid) from 2020-50. The 3.5 minutes in 2020 are the result of calibration of the model with the currently observed consumer average outage minutes in the Danish system.
- Adequacy results are very similar in project-based and offshore grid solutions, as is the overall development of the generation portfolio of wind and PV, both on system level and in Denmark.
- The results show that the domestic transmission system in Denmark is pivotal for the "Energy Not Served". The results with Eastern and Western Denmark simulated as copper plates (no constraints in

transmission) show ten times fewer outage minutes in the project-based scenario in 2020, and in practice zero in the other case.

- The future regional capacity surplus derived in the project is very pronounced in Denmark. Compared to the forecast by the Danish Energy Agency, the generation capacity in the scenarios are about 5 GW higher in 2030 in Denmark.
- Events with lack of adequacy (on system level and in Denmark) seem uncorrelated to the amount of wind and PV generation during such events. In other words, there is in general sufficiency of installed generation capacity of thermal units to secure the supply when generation from wind and PV is low.
- For Denmark in general, the events of adequacy deficit do not seem to be correlated with the available interconnector capacity feeding into the country.
- By contrast, the events of adequacy deficit (on system level and in Denmark) are to some extent correlated with the actual demand in a region: higher demand results in worse energy not served events
- On system level, most adequacy deficit events occur when system generation capacity overall is abundant, but power cannot be transported to areas which have deficit. Therefore, on system level in general, lack of available transmission capacity is the cause of “energy not served” situations.

6 References

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