Danish Energy Agency

Climate Change Agreement Analysis 1

Main Report:
Security of Electricity Supply Towards and After 2030

January 2022

Executive summary

Denmark's level of security of electricity supply (SOES) is among the highest compared to other countries that we usually use for comparison and this is expected to continue until 2030. The SOES in Denmark will be challenged in the years around and immediately after 2030, because of 1) Increase in demand due to electrification of heating and transport as well as more data centers and Power-To-X facilities. 2) Increase in intermittent renewable capacity and closure of thermal power plant. Both result in an increased probability of power shortage. On top of this, most other European countries are also in the process of installing more intermittent renewables and closing thermal production capacity.

With the *Climate Change Agreement for Energy and Industry* of 22 June 2020 and the *Climate Action Plan for a green Waste Sector and Circular Economy* of 16 June 2020, a number of initiatives were launched. The present analysis evaluates the consequences for SOES because of the initiatives in the Climate Change Agreement and other relevant initiatives, focusing on SOES. Under the Climate Change Agreement, the consequences for the district heating sector of a fossil fuel ban and reduced use of wood-based biomass should also be analysed[1].

The analysis covers the three components of SOES: resource adequacy, system security and grid adequacy. The quantitative analyses towards 2035 focus mainly on resource adequacy.

The analysis shows that Denmark can expect a high SOES towards 2030, but that brownouts due to insufficient resource adequacy will begin to happen from 2030 and onwards.

Resource adequacy

Around 2030 and onwards, situations can arise where there will be insufficient electricity production and capacity on the international connections to cover the increasing electricity demand (power shortage). Today, there are no power outages in Denmark due to lack of resource adequacy, but power outages are expected to occur around 2030 with approx. 0.3 outage minutes in Western Denmark and approx. 6 outage minutes in Eastern Denmark on average per consumer per year. The model analyses show that the number of interruption minutes will increase sharply in the years after 2030.

The power shortage is especially expected to occur during windless and dim periods during the winter, when at the same time there is not enough power to import. Electricity production from both wind and solar do contribute to the resource adequacy - but in a different way and to a lesser extent than traditional thermal electricity production. If there is already a lot of electricity production from wind and solar, then more production from wind and solar in the same geographical area will only improve resource adequacy marginally, as windless and dim periods will occur at roughly the same times as existing wind and solar power production.

The analysis of resource adequacy is based on the detailed data set used for Denmark's Climate Status and Outlook 2021[2], including the MAF2020 data set from ENTSO-E, but also including two new energy islands.

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[1] A separate report describes the general consequences for the district heating sector (price effects, security of heat supply etc.) [in Danish only].

[2] https://ens.dk/en/our-services/projections-and-models/denmarks-energy-and-climate-outlook

The interconnectors are an important part of resource adequacy under the green transition. This is because an electricity system with many interconnectors can benefit from differences in weather systems between different countries when solar and wind capacity are dispersed over larger geographical areas. Thus, high availability of the interconnector capacity is vital for SOES.

The analysis includes a number of sensitivity calculations, e.g. scenarios with higher or lower risk of power outages. The sensitivity analyses includes a possible ban on oil and natural gas in the district heating sector and a possible accelerated reduction of wood biomass in electricity and district heating production which increases the risk of power outages, cf. Table 1.

Table 1: Expected outage minutes due to lack of resource adequacy

	Western Danmark			Eastern Denmark		
	2030	2032	2035	2030	2032	2035
Baseline	0.3	3	16	5	26	172
Ban on fossil fuels 2030	1	7	38	11	44	254
Reduced biomass 2035	0.3	3	27	5	26	375
Both	1	7	62	11	44	464

Note: These outage minutes only relate to ressource adequacy and do not include outage minutes due to lack of system security or grid adequacy. In general, results are uncertain and include stochastic variations due to the use of Monte Carlo techniques.

A number of factors could potentially improve the resource adequacy relative to the baseline projection. In particular, there is an unexploited potential in increased flexible electricity demand, increased capacity on interconnectors and increased electricity savings on inflexible electricity demand.

It is not only the ability to match electricity demand with sufficient electricity production that can challenge the SOES. Outages in the electricity supply can also occur if there is insufficient capacity in the electricity grid (grid adequacy), or if the system's robustness against faults and IT incidents (system security) deteriorates.

System security

System security may be challenged in the coming years because there will be fewer thermal power plants which traditionally have stabilized the electricity system. Renewable energy production from wind and solar does not have the same stabilising properties. The Danish TSO (Energinet) works in several ways to ensure system security in a future system based on intermittent renewables. At the same time, work is being done to develop models to assess the extent of future power outages from lack of system security. At present, the models are not fully developed. However, the model shows no sign of significant increase in outages due to lack of system security.

Grid adequacy

Grid adequacy is increasingly being challenged by an ageing electricity grid, that is facing reinvestments, increased electricity consumption as well as several power plants connected decentrally. With existing investment strategies, the model shows a moderate increase in outage minutes from the current level of approx. 20 minutes to about 28 minutes around 2030.

The SOES planning target

The Minister of Climate, Energy and Utilities[3] annually sets a planning target for SOES. Most recently, the Minister announced the level for 2030 in February 2021. The planning target was set at 35 outage minutes in 2030. Today, the level of SOES is better than this planning target, as the number of outage minutes in recent years has only been around 20 on average per consumer per year.

The socio-economically "optimal" level of SOES is complicated to calculate and associated with large uncertainties. The analysis does not include such a calculation. However, socio-economic calculations and considerations about the right level of SOES become increasingly relevant with the challenges expected to arise after 2030.

[3] Website www.en.kefm.dk

Contents

1 Background

A number of new political agreements and initiatives have necessitated an analysis of SOES with updated assumptions. Thus, the Climate Agreement for Energy and Industry of 22 June 2020 and the Climate Plan for a Green Waste Sector and Circular Economy of 16 June 2020 have created a new framework for the energy system that has consequences for SOES. In addition, a number of measures can be identified that may have an impact on the SOES, including various electrification measures. At the same time, the parliamentary voting agreement of 4 June 2021 has created a framework for regulating the continuity of supply from the distribution companies, which may have significance in relation to outage minutes related to grid adequacy.

In addition, the Danish Energy Agency has published the Climate Status and Projection 2021 (KF21) in April 2021 and ENTSO-E published new scenarios in 2020, which also have consequences for assessing SOES in Denmark. Hence, there is a need to reassess the SOES with new assumptions.

The Climate Change Agreement states under the section on Green District Heating that: On that basis, an analysis is initiated to shed light on the consequences of a possible ban on oil and natural gas for district heating production from 2030, including consequences for heating security of supply, electricity and heat prices. The analysis must also assess how relevant initiatives in this Agreement will affect SOES.

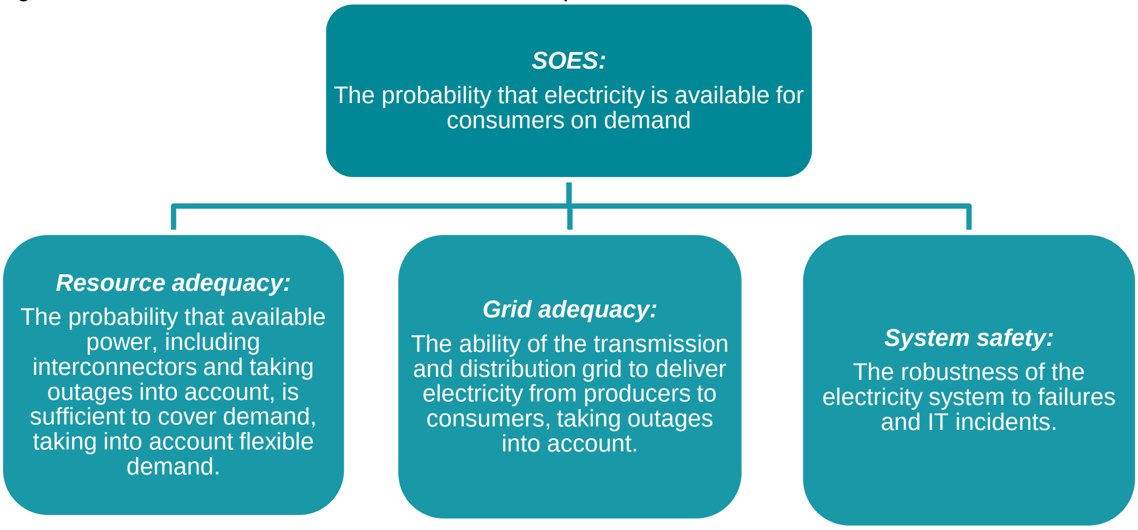
The Climate Agreement also states in the section on sustainability requirements for wood-based biomass for energy, that: The parties to the Agreement agree that the consequences of limiting the consumption of wood biomass for electricity and heat production in the long term must be considered - including effects on security of supply and costs for consumers. An analysis of relevant measures and the consequences of these must be initiated.

The present analysis assesses the consequences for the SOES of relevant initiatives, including a possible ban on oil and gas and a limitation of wood biomass. The last two are also the subject of separate and more comprehensive analyses, while only the SOES is analysed in the present report.

2 Introduction

SOES can be divided into three components: ressource adequacy, grid adequacy and system security, see Figure 2.1.

Figure 2.1: Definition of SOES and its three components



Source: Electricity Supply Act and Energinet's annual report on SOES

The analysis covers all three aspects of security of electricity supply. However, most emphasis has been placed on resource adequacy. This is because the resource adequacy is expected to be the most important factor for future challenges with SOES. The development in future resource adequacy is determined with the Danish Energy Agency's model, called Sisyfos. System security is described qualitatively in accordance with contributions from Energinet, while grid adequacy is described in accordance with contributions from Green Power Denmark[4].

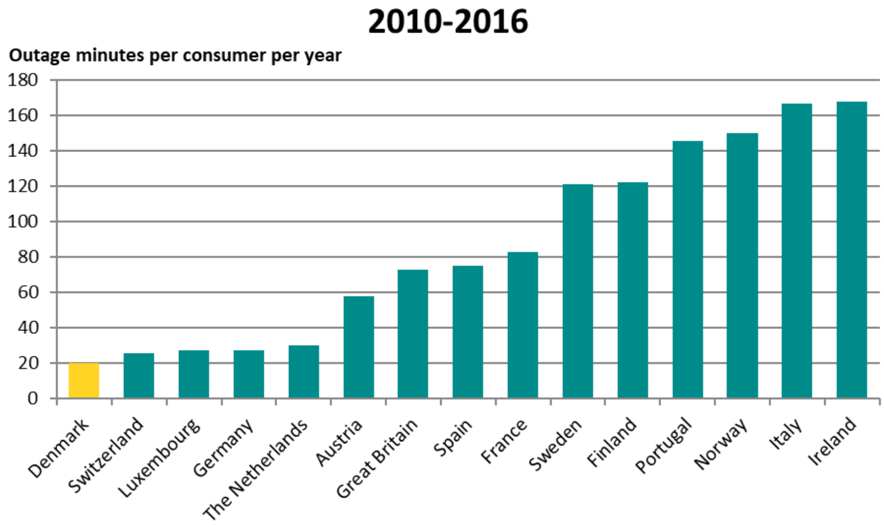
2.1 Current level and future target for SOES

Figure 2.2 shows that Denmark's level of SOES is one of the best among the countries most often used for comparison, with an average number of outage minutes around 20 minutes per year.

Today, the outage minutes originate almost exclusively from situations that arise in the network, e.g. a ruptured cable, a local short circuit or a lack of capacity on a connection. In the future, (lack of) resource adequacy is also expected to contribute to the total number of outage minutes.

[4] Until 23 March 2022: Dansk Energi.

Figur 2.2: The level of SOES in a number of countries



Source: Energinet and CEER Benchmarking Report 6.1.

The minister of Climate, Energy and Utilities announces every year in February a planning target for the desired level of future SOES, on the basis of Energinet's annual Report on electricity supply security (RSOES), cf. the Electricity Supply Act, section 27a, subsection. 3.
In 2021, the ministerial planning target is 35 outage minutes for the entire electricity system (i.e. SOES as a whole), divided into 28 outage minutes from the distribution network, 5 minutes related to resource adequacy and 2 minutes related to system security and interruption in the transmission network, as proposed by Energinet in RSOES 2020.

The current relatively high level of security of SOES in Denmark is largely a result of high prioritiy to SOES rather than being determined on the basis of a socio-economic optimisation. However, there is an increased focus on determining the recommended level based on a balance between economic advantages and costs of changes in the level of SOES.

Under the electricity market regulation (EU) 2019/943, a method has been developed in 2020 for calculating a reliability standard. A reliability standard specifies the maximum number of annual hours of outages that a country should accept, calculated on the basis of some form of cost-benefit analysis of power outages. The Danish Energy Agency is in the process of estimating the necessary inputs for a reliability standard, including a Value of Lost Load (VoLL) estimate.

VoLL is a value that expresses the socio-economic costs of outages and is defined as an estimate in EUR / MWh of the maximum electricity price that customers are willing to pay to avoid an outage. The Danish Energy Agency has conducted a quantitative survey among 1,029 households and 1,284 companies. One of the lessons learnt is that it can be very difficult for a Danish electricity consumer to set a value on a power outage. The reason may be that Danish electricity consumers very rarely experience power outages, and therefore have almost no experience with the consequences of them.

The Danish Energy Agency has therefore concluded that the socio-economically optimal level of SOES is difficult to estimate with high precision. An estimate of VoLL will create a better basis for setting the ministerial planning target for Denmark. In addition, with the voting agreement of 4 June 2021 on an efficient and future-proof electricity infrastructure to support the green transition and electrification, it has been decided that a VoLL estimate must also be used to determine the continuity of supply at the network company level, as a part of the economic regulation.

3 Resource adequacy towards 2035.

Resource adequacy is the probability that there is enough electricity production available at any given time - including possibilities for imports through interconnectors - to cover electricity demand in a given electricity price zone at all times. This section describes the resource adequacy in the years until 2035 in the two Danish electricity price zones named Western Denmark (DK1) and Eastern Denmark (DK2), under consideration of the new initiatives from the Climate Agreement 2020, Denmark's Climate Status and Outlook 2021 and updated scenarios from ENTSO-E[5].

It must be emphasized that the results of the analysis are subject to great uncertainty. On the one hand, there is uncertainty about a number of the various inputs to the model, especially the development in electricity demand and in the thermal capacity in Denmark and abroad over the next 10-15 years. In addition, the model type used, which looks for rare and extreme cases of power shortages, is very sensitive to small changes in assumptions when the system is close to its capacity limit.

Results in the report with regard to outage minutes should therefore be seen primarily as orders of magnitude and not as precise figures. The calculated changes in the resource adequacy as a result of changing assumptions or the effect of various initiatives are thus also uncertain - whereas the trend is more certain.

The assumptions behind the baseline scenario and sensitivity analyses of the resource adequacy are elaborated in the background report[6].

3.1 Assumptions

The analysis of ressource adequacy towards 2035 is based on simulations from the Danish Energy Agency's model named Sisyfos.

3.1.1 The Sisyfos model

Sisyfos is a Monte Carlo model for resource adequacy. The model is stochastic, i.e. it "rolls the dice" for a number of power lines and power plants and examines for a large number of operating situations whether the entire electricity demand can be satisfied, or whether a shortage can be expected part of the time in some electricity areas. The model is built in Excel / VBA and R and is developed by the Danish Energy Agency and the consulting firm Ea Energy Analysis.

The model calculates Expected Energy Not Served (EENS), Loss-Of-Load-Probability (LOLP), Loss-Of-Load-Expectation (LOLE), Expected Unserved Energy (EUE), outage minutes and a number of other values for the nodes included in the dataset. In this analysis, we focus on outage minutes, EENS and LOLE.

Outage minutes is defined as the number of minutes per year that a consumer or a group of consumers on average do not have access to or are not expected to have access to electricity.

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[5] ENTOS-E = European association for the cooperation of transmission system operators (TSOs) for electricity.. The Danish TSO is Energinet.

[6] (currently only in Danish) Baggrundsrapport: Effekttilstrækkelighed – Grundberegning samt følsomhedsanalyser på Sisyfos-modellen, *Energistyrelsen, januar 2022*

LOLE is the internationally used unit for resource adequacy. It is defined as the expected frequency of situations (usually in hours per year) where available production capacity in an electricity area, including the possibility of import, is less than the electricity demand in the electricity area.

There are 26 nodes in the dataset used. Five are Danish areas (Western Denmark, Eastern Denmark, Bornholm, Krigers Flak and the (future) energy island in the North Sea). The remaining nodes are Denmark's neighboring countries and a number of other countries, so that the model covers most of Europe.

The model is a purely physical-technical model, which calculates the probability of power shortage at given times, but does not calculate electricity prices etc. It also does not include system services or network adequacy. Sisyfos is described in more detail in the background report [in Danish only].

3.1.2 Assumptions in the baseline scenario

Data from Denmark's Climate Status and Outlook 2021 (KF21) is used for Denmark - with the two future energy islands as an exception. The islands are not included in the KF21 baseline scenario. In the present analysis, it is assumed that the Western Energy Island of 3 GW wind power will be connected to the Netherlands and commissioned between 2032 and 2033, while the Eastern Energy Island (Bornholm) of 2 GW wind power will be connected to Germany and commissioned between 2029 and 2030[7]. Any subsequent expansions of the energy islands are not included.

The analysis takes into account some degree of flexibility in electricity demand, as flexibility is expected to play a crucial role in security of electricity supply in the future. The detailed assumptions for the flexibility are listed in Appendix 1[8] of the background report. However, expectations of the degree of flexibility in different categories of electricity demand is very uncertain, as it is still unknown to what extent some of the new technologies can be made flexible and how people will respond to the incentives to be flexible. For this reason, in addition to the basline scenario, where a certain degree of flexible demand is assumed, two alternative flexibility scenarios have been analysed: one without flexibility and one with maximum flexibility.

The electricity demand and the production capacities abroad for 2025 and 2030 are taken from ENTSO-E's data set for the Midterm Adequacy Forecast (MAF) 2020. For 2021 it is from the data set to MAF 2019. The electricity demand and production capacity abroad for 2040 are from the data set to Ten Year Network Development Plan (TYNDP) 2020, the National Trends scenario. There is a linear interpolation between 2025 and 2030 and between 2030 and 2040.

A substantial part of the input data are climate data on an hourly basis. This applies to electricity demand, intermittent renewables and hydro. Sisyfos uses climate data for a number of different climate years to be able to simulate a given future year under different plausible weather conditions and uses climate data from the years 1985, 1987, 1996 and 2007-2015. Data are from ENTSO-E's PECD database and the background report gives the rationale behind the choice of these particular 12 climate years. The results below are thus based on an average of the simulations of the 12 different climate years, each of which has been simulated 50 times with 8760 hours in each simulation.

[7] This is the technical assumption used in this analysis. There are ongoint talks with different countries regarding possible interconnectors to the future Danish energy islands.

[8] https://ens.dk/sites/ens.dk/files/El/baggrundsrapport_kaa_1.pdf. In Danish only.

3.2 Results

3.2.1 Baseline scenario

Figure 3.1 shows the result of the baseline scenario. Until 2030, outage minutes are not expected due to resource (in)adequacy. From 2030 and onwards, outage minutes are expected, especially in Eastern Denmark (DK2), but also to some extent in Western Denmark (DK1).

Figur 3.1: Development in expected number of outage minutes due to ressource adequacy for the baseline scenario in selected years until 2035

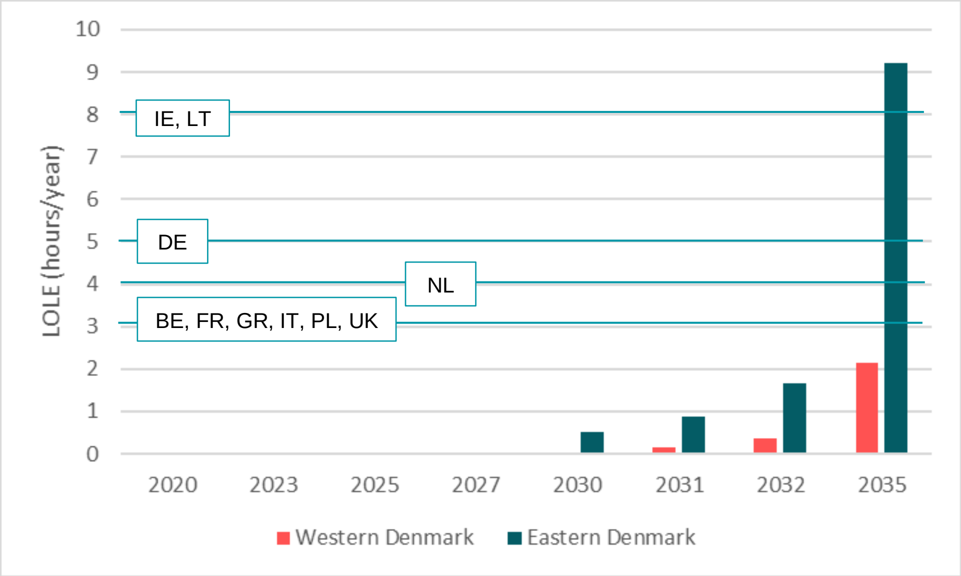
Note: The planning target applies to 2030

The calculations show that in the long term, Denmark may face outages on a somewhat larger scale than today, if no countermeasures are implemented. Historically there have been no outage minutes caused by (lack of) resource adequacy in Denmark, and only a few outage minutes caused by faults in the network, which is approximately 20 minutes on average over the last 10 years, cf. section 5.

After 2030, the power outages seem to become a lot more frequent than the Minister's most recently announced planning target for SOES of 35 outage minutes per year for the entire electricity system and five outage minutes related to resource adequacy.

Figure 3.2 shows the same trend when resource adequacy is calculated as LOLE (hours / year). LOLE is used internationally, thus allowing for international comparisons. Figure 3.2 also shows the reliability standard (RS) in a number of countries where a RS exists. The concept of reliability standard is described at the end of section 2.1. Reliability standards are specified as LOLE, if they are based on the ACER method. Denmark has not yet set a reliability standard according to the ACER method. It can be seen from Figure 3.2 that the expected number of LOLE hours in Denmark in most years are lower than the reliability standards in the specified countries, but in 2035, the figure for Eastern Denmark will be above the highest RS in the European countries, which are used for comparison.

Figure 3.2: Expected development in LOLE (hours/year) in selected years towards 2035, including reliability standard in selected European countries.



The resource adequacy challenges can largely be attributed to the closure of several major thermal power plants in Denmark, which will take place in the period up to and just after 2030 combined with an expected increase in electricity demand due to electrification of the heating and transport sectors, as well as Power-to-X (PtX) [9], data centers, etc.

The trend towards reduced resource adequacy will be either enhanced or weakened by some of the initiatives in the Climate Change Agreement of 22 June 2020. There are several initiatives that can lead to increased electricity demand. Those are reorganization of heating taxes, support for phasing out oil and gas boilers - both of which can increase the number of heat pumps - as well as incentives to choose electric cars, subsidy schemes to support CO_2 capture and storage technologies or PtX all of which increase electricity demand.

On the other hand, there are initiatives that increase electricity production through support for renewable energy sources. However, this may have a limited impact on resource adequacy because of their intermittent nature. At the same time, the funds earmarked for energy efficiency improvements in the Climate Agreement of 22 June 2020 is expected to contribute to increased resource adequacy. The various initiatives from the Climate Agreement, which are included in the data set for KF21, can be found in a background note 2A to the KF 21 projection [in Danish only].

The reduced amount of waste incineration in Denmark, which is planned with the Waste Agreement of 16 June 2020, can also be assumed to have a negative impact on resource adequacy. Calculations on Sisyfos, however, show that the effect of ~30 pct. lower incineration capacity in Denmark, as stipulated in the agreement, is moderate.

[9] Power-to-X (PtX) refers to technologies, where electricity is used to produce fuels or other chemicals. A common feature is production of hydrogen by electrolysis, where water is split into hydrogen and oxygen, using electricity. The hydrogen can then either be used directly or processed further to e.g. ammonia or carbon based chemicals or fuels.

3.2.1.1 Foreign dependency

Denmark's current level of resource adequacy is very high, despite the high share of renewable energy in electricity production (in 2020, wind power accounted for about 48 per cent of the domestic electricity supply). The high level of resource adequacy is due in part to the existence of many interconnectors. Denmark currently has interconnector capacity corresponding to more than 50 per cent of domestic production capacity (the target for all EU Member States by 2030 is a minimum of 15%). The large interconnector capacity enables trade of large amounts of electricity with other countries, which is an effective way of reducing the consequences of the fluctuations in electricity production from solar and wind. On the other hand, Denmark is becoming more dependent on the ability to trade electricity.

In order for the interconnectors to benefit the Danish SOES, it is essential that the capacity made available on the connections is high. Currently, this is not always the case because some countries priorities to first solve internal congestions in their network. There is a requirement in the EU that a minimum of 70 % of the interconnector capacity must be made available to the electricity market. This requirement is not directly modelled in the analysis, since it is not known how the requirement actually affects the availability during the hours with power shortage.

Figure 3.3: Histogram of power surplus based on ~5 million simulated operational states in 2035

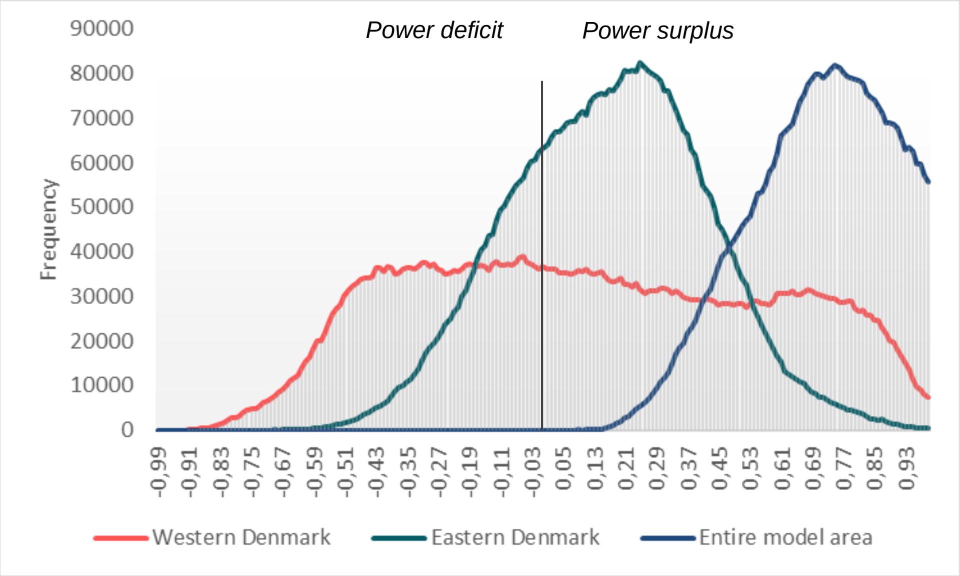


Figure 3.3 illustrates foreign dependence. The figure shows the frequency of operational states with power surplus and deficit in Western Denmark, Eastern Denmark and in the entire modelled area (ie most of Europe) for the year 2035. This means that the area under the curves sums up to more than 5 million operational states. The part of the area below the curves to the left of the vertical black line is the number of situations where there is insufficient power in the area to meet the demand. Thus, in all these situations, there is a need to import electricity from other areas.

Based on Figure 3.3, it can be seen that power deficit in Western Denmark is quite frequent. The same applies to Eastern Denmark, but to a lesser extent than in Western Denmark. There is no direct link between power deficit or power surplus in an area and the resource adequacy, because electricity ususlly can be imported to handle a power deficit. The reason that resource adequacy in Western Denmark is better than in Eastern Denmark is that Western Denmark has more interconnectors.

The possibility of electricity imports depends on the existence of a power surplus in another country nearby and sufficient available capacity in the interconnectors. One of the interesting simulation results for 2035 is that in the entire model area appears to be at a power surplus at all times. Hence, power shortages in different electricity areas are due solely to limitations in the national grids or interconnectors.

It should be noted that in each hour there must be a balance between production and consumption, thus there cannot be a power surplus in practice. The model assumes that the market creates this balance, whenever it is possible.

3.2.1.2 Comparison with Energinet's projections

Energinet publishes an annual report on SOES which also presents projected resource adequacy results. Comparing Energinet's results with the Danish Energy Agency's can be useful, as it can help to illustrate how different assumptions, data inputs and model properties can affect the results.

Over the last few years, Energinet's calculations have shown a higher number of outage minutes than found in the present analysis. However, in Energinet's 2021 report calculates fewer outage minutes are than before and slightly fewer than in the present analysis, but both calculations show a trend towards more outage minutes after 2030. However, since Energinet has not calculated the resource adequacy after 2031, it is not clear whether the large increase in outage minutes towards 2035 seen in the present analysis will also occur with Energinet's model and assumptions.

The differences between the results of Energinet's and the Danish Energy Agency's calculations can largely be attributed to the fact that different data have been used for Denmark. Energinet has used earlier data published by the Danish Energy Agency (the so-called 2020 Analysis Assumptions), while the Danish Energy Agency has used data from Denmark's Climate Status and Outlook from April 2021. One difference is that one of the energy islands comes into operation earlier in Energinet's data than in the Danish Energy Agency's data. These factors are considered the primary reasons for fewer outage minutes in Energinet's results. Moreover, Energinet has used certain unpublished data from the so-called PEMMDB database, where the Danish Energy Agency has relied on published data. The latter is considered to be of less importance.

3.2.1.3 When will outage minutes occur?

Based on the many simulated operational states in Sisyfos, it is possible to extract results on which months and which hours during the day, outage minutes are most likely to occur. The picture is rather clear: Outage minutes will be most frequent in December, January and February, and in the hours between 4 and 8 pm[10]. Furthermore, Sisyfos has been used to assess the *duration* of the expected, future interruptions. It seems that interruptions will typically be of a few hours duration, related to the afternoon peak demand, but also that longer interruptions can occur.

3.2.2 Sensitivity analysis

Calculations of the resource adequacy 10 years or more into the future are inevitably subject to great uncertainty. To illustrate how assumptions about the future affect the results, a number of sensitivity calculations of alternative scenarios have been made. In addition, the effect on resource adequacy of the two proposed measures from the Climate Agreement of 22 June 2020, i.e. a possible ban on the use of oil and natural gas in district heating from 2030 and a reduced consumption of wood biomass in electricity and heat production from 2035, have been calculated.

The figures in this section usually show results for 2030, because the uncertainty associated with the results is smaller in 2030 than in 2035. In some cases, more years are included in the figures. The effects of the energy islands are shown for 2032, as both islands are only assumed to be in operation around 2032.

3.2.2.1 Ban on fossil fuels

With the Climate Agreement of 22 June 2020, it was also decided to analyse the consequences of a possible ban on oil and natural gas for district heating production from 2030. The results of this analysis is described in detail in a separate report on *a possible ban on oil and natural gas in district heating production and limitation of wood biomass for electricity and district heating production* [in Danish only]. The effect on resource adequacy of such a ban is analysed as a sensitivity to the baseline projection described above.

[10] The background report (in Danish only) provides more detail.

A ban on fossil fuels in district heating is expected to have a significant negative impact on resource adequacy in Denmark after 2030, with more outage minutes than what the baseline scenario predicts, especially in Eastern Denmark. Figure 3.4 shows how the level of outage minutes is expected to increase from 2030 to 2035 in four different scenarios, including the fossil fuel ban scenario.

The reason why a fossil fuels ban will have such a decisive effect on the resource adequacy is that the combined heat and power plants that use fossil fuels today contribute with controllable electricity production. Controllable electricity plants will be more valuable as solar and wind increase their share of electricity production, while electricity demand is rising.

Part of the rising electricity demand will be from electrical heat pumps or electrical boilers in districit heating units that may replace CHP plants. This will have a negative impact on ressource adequacy[11].

3.2.2.2 Wood-based biomass

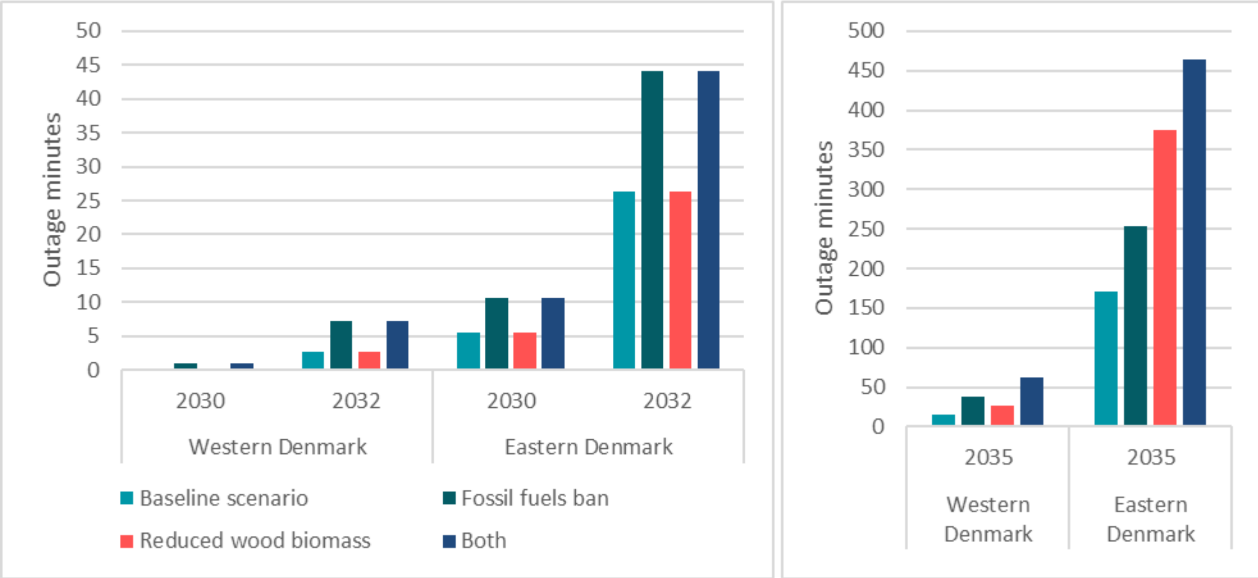
With the Climate Agreement of 22 June 2020, it was also decided to analyse the consequences of limiting the consumption of wood biomass for electricity and heat production. The results of this analysis is described in detail in a separate report on *a possible ban on oil and natural gas in district heating production and limitation of wood biomass for electricity and district heating production* [in Danish only]. The effect of a reduced amount of wood biomass for electricity and heat production on resource adequacy is analysed as a sensitivity to the baseline scenario described above.

Figure 3.4 shows that when comparing the baseline scenario with a scenario where wood-based biomass is phased out then the level of outage minutes is expected to be higher in 2035, both in Western and in particular Eastern Denmark. This can largely be attributed to the fact that the biomass reduction will lead to the closure of the most central power plants on Zealand.

Figure 3.4 also shows the result of a combination scenario in which *both* the fossil ban and the reduced amount of wood biomass are imposed. This scenario creates an even greater challenge in 2035 with resource adequacy, because a combination of the two restrictions results in even less controllable electricity production. There is uncertainty in the calculated outage minutes due to a number of data uncertainties. However, the overall trend with increasing outage minutes - especially in the combination scenario - is robust, since this trend is a consequence of the closure of thermal capacity combined with increased electricity demand - both in Denmark and abroad. The same trend is seen in Energinet's calculations, although these have a time horizon ending in 2031.

[11] Note that individual heat pumps may may have a higher efficiency than centralised heat pumps with district heating because district heating network losses are avoided. On the other hand, centralised heat pumps are expected to be significantly more flexible, and therefore better for overal ESOS.

Figure 3.4: The effect of a ban on fossil fuels from 2030, reduced wood-based biomass from 2035 and the combination of these two



Note: The figure is divided into to parts due to the large number of outage minutes in 2035.

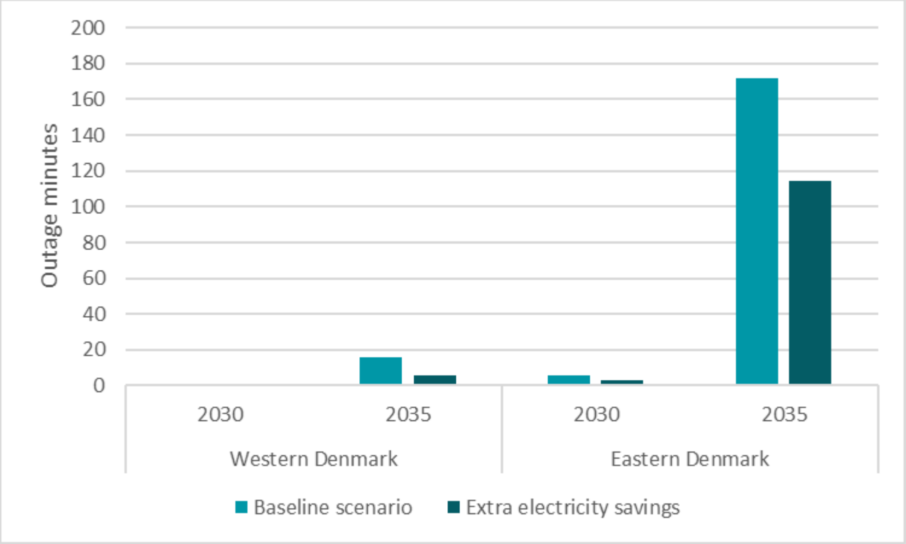
3.2.2.3 Electricity savings

In the baseline scenario, a steep increase in electricity demand is assumed, cf. Denmark's Climate Status and Outlook 2021. Additional electricity savings on the inflexible part of electricity demand will improve security of electricity supply. An alternative scenario has been set up, in which further electricity savings of almost 9 % are assumed in 2030, compared to the baseline projection. A reduction of that magnitude requires implementation of further measures. New such measures are in the pipeline, in part at a European level.

Figure 3.5 shows the result of the sensitivity analysis, indicating a very strong reduction on the number of outage minutes both in 2030 and in 2035[12] as result of extra electricity savings.

[12] The calculation does not include a rebound effect where lower demand can lead to lower electricity prices and reduced incentives to invest in production capacity.

Figure 3.5: The effect on ressource adequacy of extra electricity savings



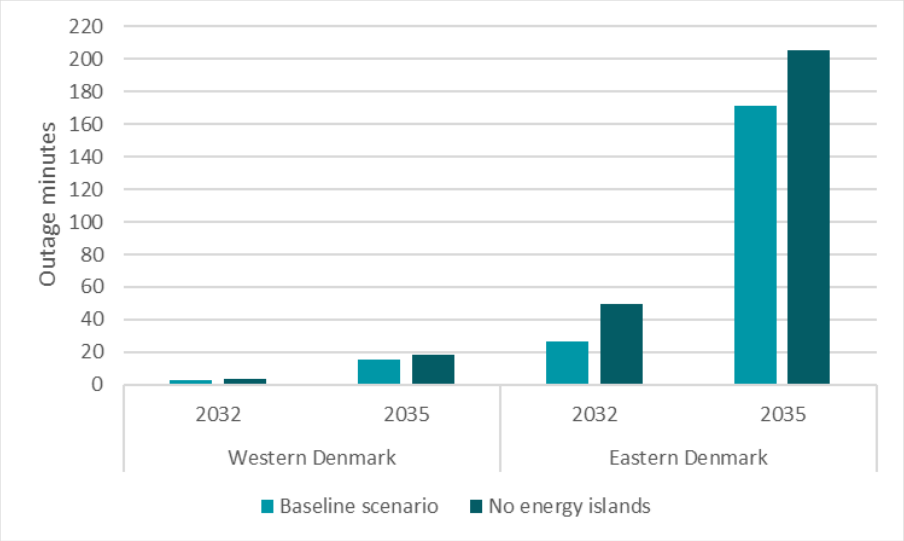
3.2.2.4 Energy islands

In KF21, the energy islands are not included in the baseline scenario, since it only includes measures where specific instruments for realization have been adopted. However, the energy islands are included in the baseline calculation in the present analysis, as they are politically decided under a number of assumptions. However, there may be uncertainty about exactly when the energy islands will be built, and this has implications for the SOES. A sensitivity calculation has been made, illustrating what would happen in the event that one or both islands are not commissioned as expected.

Figure 3.6 shows that the absence of both energy islands without countermeasures will have a negative impact on the resource adequacy in Eastern Denmark. The positive effect of the energy islands can largely be attributed to the extra interconnectors that are associated with the islands. The increased electricity production from the offshore wind turbines on the islands also makes a contribution to the resource adequacy – but to a lesser extent.

An analysis has also been made of alternative destinations for interconnectors with connections to Poland instead of Germany for the eastern island and Belgium instead of the Netherlands for the western island. However, these changes only affect the resource adequacy marginally.

Figure 3.6: Effect on resource adequacy of the two energy islands in 2032 and 2035



3.2.2.5 Flexible demand

One of the big unknowns in the future electricity system is how much flexibility in electricity demand will be realised. The baseline scenario assumes a certain degree of flexibility, especially in electricity demand from PtX systems, but also from collective heat pumps and electric boilers, as well as electric cars and individual heat pumps. The detailed assumptions can be found in the background report (in Danish only).

Two alternative scenarios illustrate the effect of demand flexibility: One with maximum flexibility and one without flexibility. The baseline scenario is expected to represent the most realistic development of future flexibility.

Figure 3.7: The effect on resource adequacy of various degrees of demand flexibility

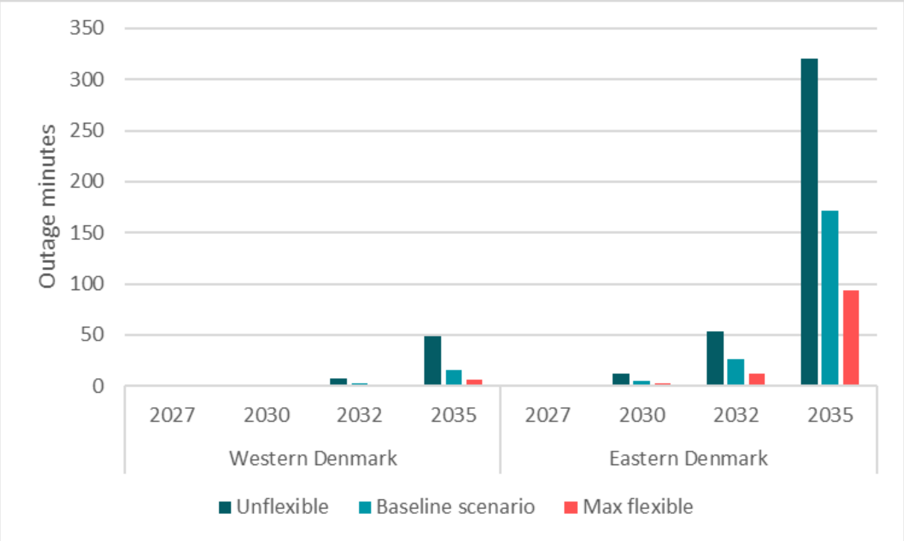


Figure 3.7 shows that the inflexible scenario implies a very bad resource adequacy, whereas the scenario with maximum flexibility improves resource adequacy significantly.

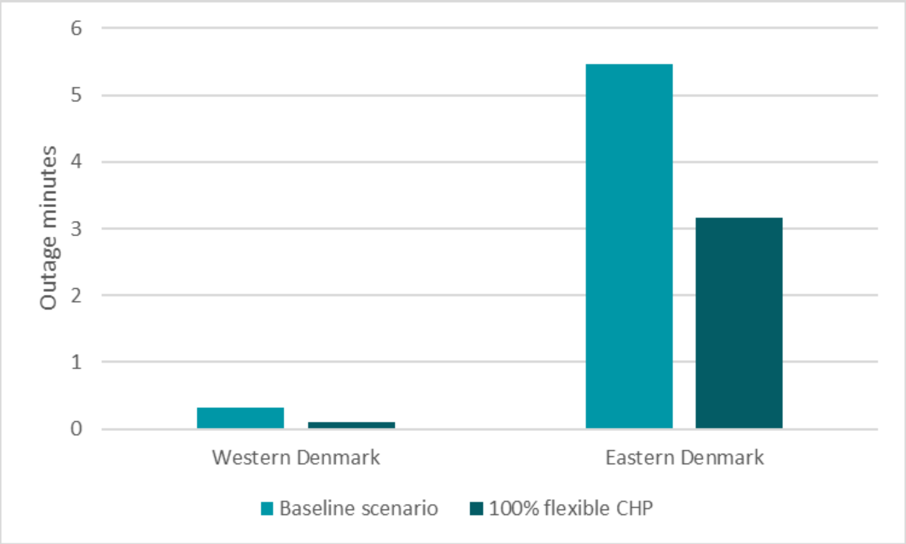
Additional sensitivity calculations have been made of different scenarios for the electricity demand in PtX plants[13]. If the PtX plants are not fully flexible, then the amount of electricity consumed in these plants will also deteriorate resource adequacy, as PtX is very electricity-intensive.

3.2.2.6 Heat dependence

Many of the Danish combined heat and power plants have a more or less fixed ratio between electricity and heat production. This means that a large part of the thermal electricity production is linked to district heating production. This link can be changed technically by establishing additional heat storage or by carrying out other conversions (heat bypass) of the CHP plants.

Figure 3.8 shows the effect on resource adequacy of making *all* the CHP plants independent of the heat production. The sensitivity thus illustrates the largest possible change of outage minutes from reduced heat dependence.

Figure 3.8: The effect on resource adequacy of removing heat dependence from all CHP plants in 2030

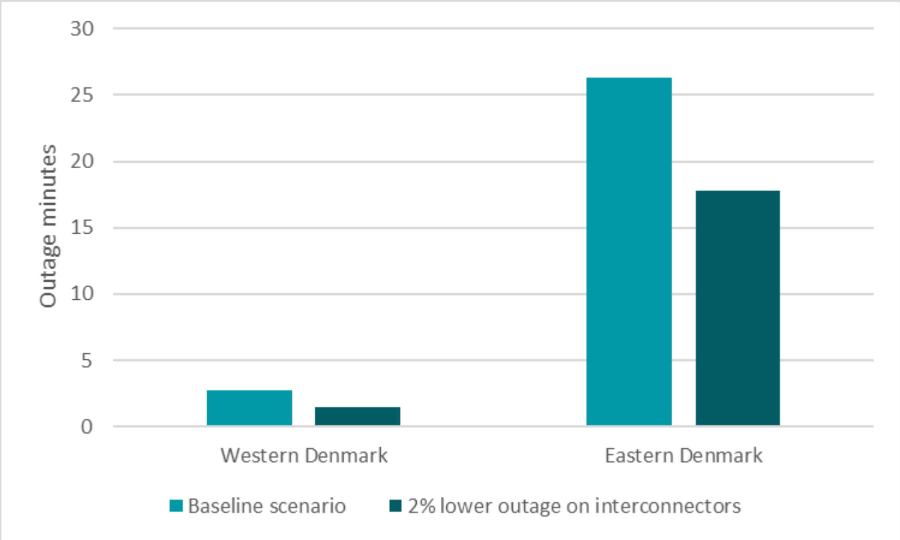


3.2.2.7 Interconnectors

There is some uncertainty on future outage on the interconnectors. The amount of outages in the baseline scenario includes the effect that internal bottlenecks in some countries limit the capacity of the interconnectors. There is uncertainty involved in the outage assumptions. Figure 3.9 shows that a 2 percentage points lower outage (compared to the baseline's 10 per cent for HVDC (high voltage direct current) and 8 per cent for AC (alternating current)) gives a significantly lower number of outage minutes in 2032. Roughly the same relative effect is seen for 2030 and 2035.

[13] The analysis is described in the background report (in Danish only).

Figure 3.9: The effect on ressource adequacy of lower interconnector outage in 2032



3.2.3 The importance of electricity demand

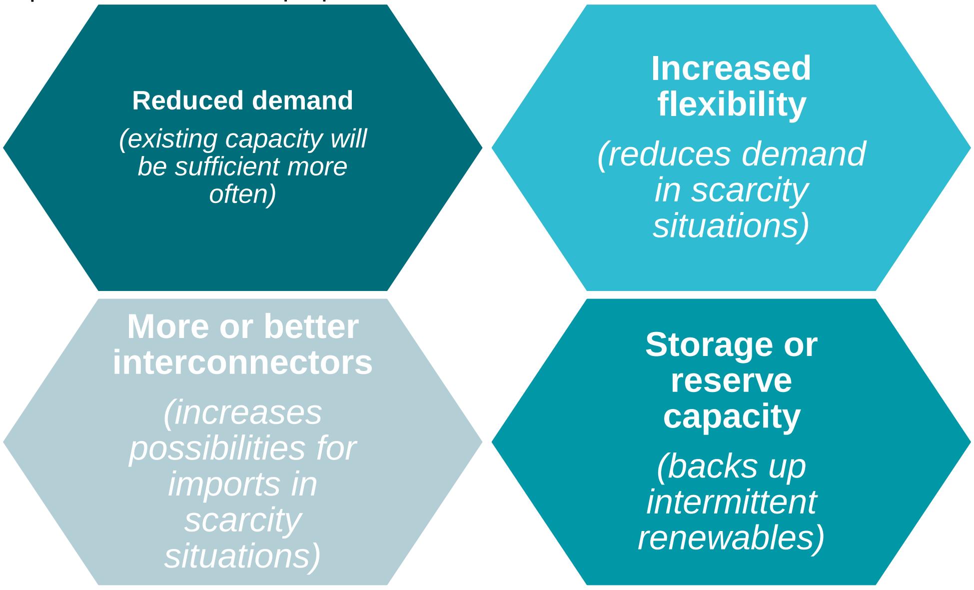
The green transition involves an electrification of energy demand. Therefore, a significant increase in electricity demand is expected in the coming decades. The magnitude of electricity demand is, of course, of great importance for the SOES. Nevertheless, the more flexible the consumption, the less the impact on the security of electricity supply. The new electricity demand is expected (with the exception of the data centers) to be more flexible than the classic electricity demand.

As there are uncertainties in the magnitude of future electricity demand as well as the degree of flexibility, a number of sensitivity analyses have been performed. The sensitivity analyses all relate to the impact of flexible electricity demand on resource adequacy and the conclusions are:

- Savings in the inflexible electricity demand have been addressed earlier and will have a positive effect.
- Increased flexibility has also been addressed earlier and also has a positive effect (and vice versa).
- A number of sensitivity calculations have been performed with more Power-to-X. These show a low impact on power adequacy because Power-to-X is assumed to be almost fully flexible. A sensitivity with fewer data centers has been performed. This has a clear positive effect on resource adequacy, as data centers use large amounts of electricity but are expected to be very inflexible.
- It is estimated that CCS will have a limited impact on the resource adequacy, as it will typically be possible to decouple CCS electricity demand for a few hours during power failure.

3.3 Possible areas of action

Resource adequacy can be affected (improved) in the future by a number of possible measures. See figure below. A number of these are addressed by various sensitivity analyses. In the present analysis, no specific measures are proposed.



4 System security

System security can be understood as the stability of the electrical system both in normal operation, in the event of operational incidents such as accidents, short circuits, lightning strikes, etc. and in the event of major blackouts (uncontrolled interruptions of electricity customers). System security is handled by Energinet. Stable operation means that voltage and frequency stay within set bands, and that during fault situations the system is always ready to handle the next fault. In addition, the electrical system must be able to be restarted in the event of a blackout. Interruptions related to system security at transmission level in recent years have typically been relatively rare and brief - and often related to minor breakdowns.

Energinet handles system security by:

- Grid connection requirements for the electricity producers and consumers. The individual systems must be robust in case of incidents in the electrical system. The grid connection process includes a number of simulation and calculation-based analyses and a number of practical plant tests. In addition, incidents that have led to unexpected behavior at one or more facilities are followed up upon. Both calculation and testing methods are continuously developed. In the future, ongoing periodic inspections of selected plants are also expected.
- Purchase of system services on the market, e.g. services that enable system restoration in case of a blackout or frequency products such as Fast Frequency Reserve (FFR) that help stabilise frequency (by up- and down-regulation of production or demand).
- Operation of integrated network components (synchronous compensators, etc.), i.e. components that can provide other necessary technical services that Energinet itself can set up in different places in the network to ensure stable operation.

4.1 System security challenges during the green transition

As the green transition progresses, a number of the plants that contribute to stability in the electricity system today are being phased out, namely the central power plants' directly connected synchronous generators with large rotating mass and their ability to support the voltage. The phasing out of thermal power plants and the introduction of large amounts of solar and wind systems, as well as new demand from PtX systems and data centers (inverter / converter connected systems) will challenge the frequency stability and the so-called system strength. The system strength expresses how large voltage changes occur as a result of a fault or disturbance in the electrical system. The system strength has previously been considered equivalent to the short-circuit current, but in a future electrical system dominated by systems connected via power electronics (inverters and converters), this is no longer the case. The system strength is expected to be challenged by phasing out the thermal plants and introducing more inverters and converters.

There are generally two possible solutions to this problem, and the optimal solution will probably be a combination of the two:

- The first solution is that intermittent renewables such as wind and in the long run also demands such as PtX contribute to keeping the electricity system stable. The new plant types do not naturally have the same stabilizing properties as power plants, but they can in some cases be supplied with such properties through the development of new control systems. Access to these properties can either be specified through network connection requirements or provided by establishing markets (system services) that motivate plant owners to establish the desired functionality. Research into these technologies is being conducted, and their availability in the new renewable energy plants is expected to emerge over the coming years. It is also expected that renewable energy plants can contribute to e.g. restarting the system after blackout, as the geographical spread of large offshore wind farms will in the long run be so great in Denmark that the service could potentially be obtained from renewable energy plants alone, if the right provisions are made in time.

- The second solution is to establish additional integrated network components (e.g. synchronous compensators) with advanced stabilizing properties. This can be economically advantageous or even necessary to maintain a secure electrical system. This can be done for system services or plant properties that renewable energy plants will not be able to provide, or where it will be extra costly to supply them from renewable energy plants.

4.2 Analysis tools and international cooperation

It is necessary to be able to predict the dynamic behavior of the electrical system from a few seconds before the moment of operation to several years ahead in time to ensure system security. The stability analyses of the electrical system conducted by Energinet are already complex today, and they require specialist knowledge as well as specialized tools. As the green transition progresses, more data and more digitalisation is therefore needed, as well as development of new analysis tools, so that the operation of the future green power system can be predicted. This allows for appropriate plant specifications, grid connection requirements, fully integrated grid components and / or markets can be established in a timely manner. Energinet is in the process of developing analysis tools for this purpose.

There is a very large focus worldwide on developing these analysis tools, and Energinet is actively participating in this work in several contexts. Partners in such work streams are other TSOs, software developers, plant developers, component manufacturers and universities. Denmark is not the only country in the world with an ambitious climate agenda. Energinet seeks cooperation with the most progressive countries and has recently established the Global Power System Transformation Consortium (G-PST) together with a number of other system operators and research institutions. The collaboration shares knowledge and develops solutions with the Irish, English, Australian, Californian and Texan system operator. G-PST has a special focus on developing the analysis tools of the future, methods for secure integration of inverter-based RE systems etc.. In addition, Energinet works closely with the Nordic TSOs and a number of TSOs in continental Europe.

The results of these works are published and implemented on an ongoing basis. In 2023, Energinet expects to be able to present a guide for the process up to 2030 based on preliminary results.

It is therefore too early at this stage to make forecasts of outage minutes due to lack of system security. However, Energinet sets - as a planning goal - one outage minute until 2030 in the Security of Electricity Supply Report for 2021. It is thus a very limited contribution to the interruption minutes that is expected from (lack of) system security if the new challenges are handled as described.

5 Grid adequacy towards 2030

This section deals with the contribution of distribution networks to outage minutes. The section is based on the text and analysis that Green Power Denmark[14] has provided to Energinet on the basis of information from the distribution companies to be used in Energinet's 2021 Report on Security of Electricity Supply. No separate analyses have been made of the grid adequacy in connection with the present analysis.

5.1 Historical contribution from the grid to outages minutes

In Figure 5.1, the historical SOES is shown as the average number of outage minutes per customer (SAIDI[15]). It can be seen from the figure that the average annual number of outage minutes has been fairly stable (around 20 minutes) for the last 13 years. All outage minutes, with the exception of the major blackout in September 2003, are due to the distribution network.

The Danish electricity supply security is one of the highest in Europe. This is mainly due to the underground cabling of overhead lines in the electricity distribution networks, which has made these networks more resilient to weather-related events.

There is a tendency for an increase in the number of unannounced interruptions, which is mainly due to faults on older 10-20 kV oil-paper-insulated cables (APB cables) and their accessories (joints). The aging of the cables means that they are less robust against mechanical influences (excavation work, pressure effects from traffic and punching, earth shifts, short-circuit currents, etc.) as well as electrical influences (e.g. overvoltage). Another challenge is the connection between (old) APB cables and (new) PEX cables, which are used today to repair faults on APB cables.

Components will typically have a higher error rate in the first years after commissioning. After this, the accident frequency drops to a lower level - only to increase again when the component becomes old and approaches replacement.

A large variation in the outage minutes between the individual grid companies is observed. This can be due to the period in which the historical expansion of the electricity distribution networks took place. The grid expansion in Denmark has thus taken place geographically at different paces, which is why the electricity distribution networks are at different stages in their life cycle. This is also reflected in the relationship between urban and rural areas, where it is often urban grid components that are older (more APB cables) and thus have a higher failure probability.

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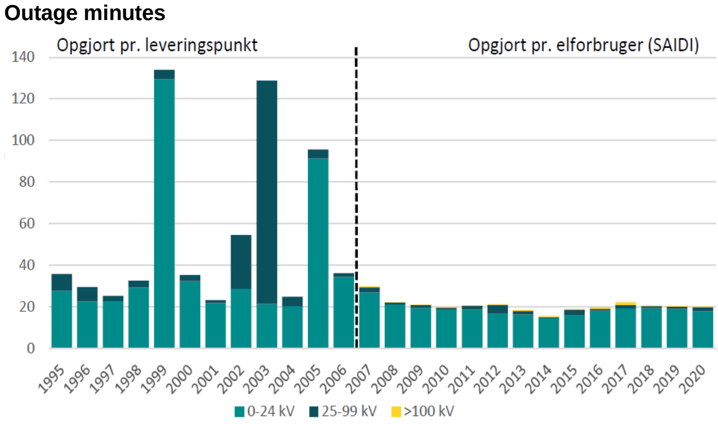
[14] Until recently: Dansk Energi.

[15] SAIDI: System Average Interruption Duration Index, i.e. an indeks for average duration of inerruprions.

Figure 5.1: Historical SOES



Source: Energinet through Green Power Denmark and distribution company failure statistics (ELFAS)

5.2 Expected development in outage minutes from the distribution grid

In connection with the preparation of the Security of Electricity Supply report for 2021, Green Power Denmark[16], together with the distribution companies, has made a projection of the supply security in the electricity distribution network. The projection is based on a model including grid data from seven network companies covering 79% of the electricity customers.

The projection of grid related outage minutes in the model is prepared with input from the age profiles of the networks, age-dependent fault probabilities (only for 10-20 kV cable systems) and the number of installed components. The model is used to estimate the increase in future faults and thus outage minutes. The age profiles are based on input from all the participating seven grid companies, which for 10-20 kV cable systems cover approx. 80% of the plant mass in the distribution networks. The age-dependent error probabilities are based on input from four network companies, which cover 41 % of 10-20 kV APB cable systems and 18 % of 10-20 kV PEX cables in Denmark. The four companies cover approx. 43 % of the electricity customers.

Increased utilization of the networks has been taken into account by using a load-dependent fault frequency for 10 kV joints. For all other network components in the model, a load-dependent error rate is not included, although for many of the other network components there is probably an increased probability of error when the load increases and approaches the capacity limits of the components. The modeling of the significance of the load is associated with uncertainty. Partly because there is a general lack of good data for this and partly because only few studies have been found on this. The inclusion of a contribution from an increased electricity demand to the year's projection of the outage minutes is therefore a subject to future improvements. The increase in electricity demand is taken from the Danish Energy Agency's Analysis Assumptions 2020.

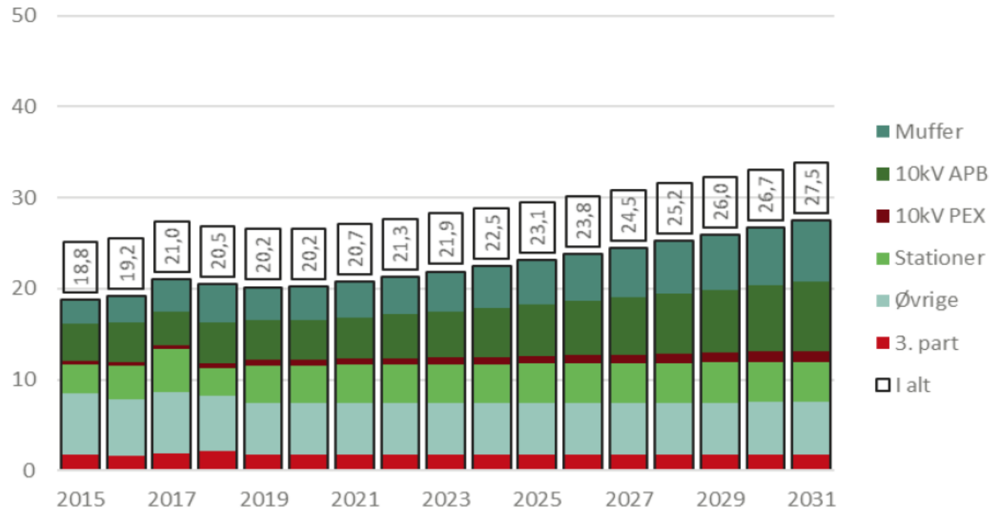
The projection, shown in

[16] Until recently: Dansk Energi

Figure *5.2*, includes contributions to outage minutes from the expected increase in electricity demand over the coming years.

Figure 5.2 Forecast of outage minutes from the distribution grid.

Outage minutes



Source: Green Power Denmark.

The projection thus shows an expected increase from the current level of approx. 20 outage minutes annually to 27 outage minutes annually around 2030. Of the 27 outage minutes, approx. 2.5 minutes are due to increased electricity demand.

The projection is made on the assumption of a reinvestment level of DKK 1.6 bn. annually until 2031. This is exclusive of approx. 200 million DKK for 30-50-60 kV lines (cables and overhead lines).

On 4 June 2021, a voting agreement was made in Folketinget, called: An efficient and forward-looking electricity infrastructure to support the green transition and electrification. The agreement entails, among other things, a new model for regulating the network companies' continuity of supply after a socio-economic balancing of costs by improving the network on one side in relation to costs for consumers due to lack of electricity on the other side. It is expected that the new model for regulating continuity of supply may result in a limited increase in the number of interruption minutes from the distribution network. There is currently no quantitative estimate, partly because the value of lost load (VOLL) is not very well known. The presumption, however, is that part of the expected increase in the outage minutes, which is shown in Figure 5.2, contains the effect of the voting agreement of 4 June 2021.

The voting agreement also sets out a number of measures to ensure that there is the right framework for the network companies to support electrification by balancing between timely and efficient investments and cost-effective operations. The measures include the implementation of an electrification surcharge by a combination of an automatic indicator and application-based surcharges, an analysis of whether the network companies have structurally increasing investment costs, due to e.g. increased digitization, which is not handled in the economic regulation and an analysis of digitization in the electricity distribution network. The measures are believed to contribute to a continued high continuity of supply, and can thus have a positive effect on the grid adequacy and thus the total SOES.

The projection includes regional differences. In Western Denmark, there is an expected increase from approx. 16 outage minutes today to approx. 20 outage minutes in 2030. In Eastern Denmark, there is expected an increase from approx. 25 outage minutes today to approx. 38 outage minutes in 2030. The difference between Western Denmark and Eastern Denmark is due to the age of the grids. There are also differences between the individual companies inside each of the two electricity areas. Thus, there are companies in Western Denmark that fit better into the projection for Eastern Denmark and vice versa.

The projection includes use of remote-controlled and monitored network stations. These network stations can help reduce the downtime associated with certain types of unannounced outages. The use of remote-controlled and monitored substations will only have an effect on the *duration* of unannounced interruptions due to faults in 10-20 kV cable systems, which are the primary contributor to the expected increase in the outage minutes up to 2031. The measure is therefore considered to be effective, and it is already used today by network companies to handle an expected increase in outage minutes. The *frequency* of unannounced interruptions will not be affected.

By *voluntarily* reducing or interrupting electricity consumption during periods of high load, security of supply can be improved. Specifically, this can be done by giving electricity customers an incentive to reduce consumption at times when the grid is particularly congested – e.g. by time-of-use tariffs or by market solutions for flexibility, eg agreements with aggregators or battery operators. There may also be interruptability agreements with individual customers. However, flexibility products also carry a certain risk: If a flexibility service is not delivered at a required time, it may lead to increased downtime, because some electricity customers will have to be switched off to protect the network (brownout). Increased flexibility is not included in the projection of grid adequacy projection mentioned above.

Other factors such as more frequent extreme weather events such as storm surges are not included in the assessment. These incidents are also expected to affect the number of outage minutes. Conversely, the positive effects of efficiency and innovation are not taken into account either. The remotely read electricity meters, which almost all customers have today, will provide significantly better knowledge of the load on the electricity grid, which will enable targeted investments and more operating solutions that can be deployed temporarily.

The projection has been implemented for Denmark as a whole and on the basis of the total investment budget for all grid companies as a whole.

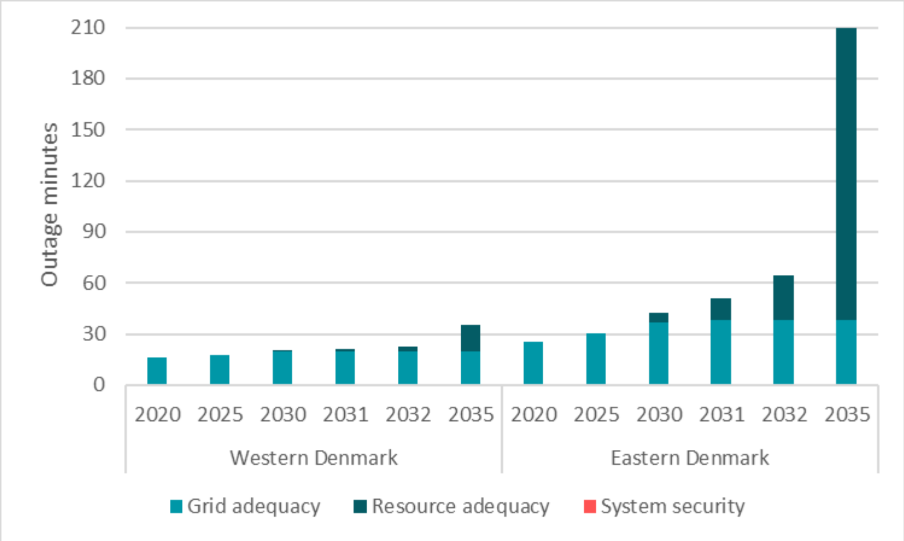
As for distribution networks, large reinvestments in the electricity network will also be needed at transmission level in the coming years. Although the majority of the outage minutes can historically be attributed to the distribution networks, interruptions in the transmission network could potentially have major consequences. Energinet is responsible for ensuring that the necessary reinvestments are made in the transmission grid in order to maintain a high grid adequacy at transmission level.

6 Total SOES towards 2035

Overall, the Danish SOES is one of the highest in Europe today, and only a slight reduction is expected for the rest of the decade primarily caused by a few outage minutes from the grid. However, SOES is expected to be challenged by several different factors after 2030: increased electricity demand caused by the electrification of society, closure of thermal power plants and a larger share of solar and wind energy in electricity production, which is less controllable than thermal power plants.

The deterioration of SOES after 2030 is expected to be mainly due to resource adequacy, but more outage minutes from the electricity grid are expected as well as some challenges with system security.

Figure 6.1*: Total number of projected outage minutes in Eastern and Western Denmark, selected years*



Note: For the ressource adequacy, results from the baseline projection are used. For grid adequacy the number of outage minutes are assumed not to change after 2031. 2020 numbers are statistical, the remainder are projection.

The system security is challenged by fewer power plants - that can offer stability services - and the connection of more renewable energy to the system. Energinet works in several ways to ensure system security also in a system based on RE. At the same time, work is being done to develop models to assess the extent of future outages due to (lack of) of system security, but at present the models are not fully developed. However, it is estimated that there will be no sharp increase in system security related interruptions.

Grid adequacy is challenged by an electricity grid facing reinvestments and increased electricity demand as well as several decentrally connected electricity generation plants. The expected increase in outage minutes presented above is from the current level of approx. 20 minutes to about 28 minutes in 2031.

Resource adequacy is expected to deteriorate significantly after 2030. Calculations on the Sisyfos model show an increase from the current level of zero outage minutes per year to approx. 170 in Eastern Denmark. This increase is based on Denmark’s Climate Status and Projection 2021 and ENTSO-E's international data from Mid-term Adequency Forecast 2020.

As indicated by the sensitivity calculations, a number of factors could reduce resource adequacy further, including in particular a possible ban on oil and natural gas in district heating and a possible limitation of wood biomass in electricity and district heating as well as absence of the energy islands and the associated interconnectors.

However, there are also factors that can improve the resource adequacy, including increased flexible electricity consumption, improved interconnectors and electricity savings in the inflexible electricity demand.

Many assumptions are uncertain in this type of calculations. Hence, the numerical results are also uncertain. Nevertheless, the general trend that SOES in Denmark will deteriorate, without counter measures, appears solid.

7 Glossary and abbreviations

CCS: Carbon Capture and Storage.

Climate year: A historical year with a corresponding set of hourly time series for wind, solar, demand etc. The Sisyfos model uses time series forom the pan-euaropean climate database, published by ENTSO-E.

EENS: Expected Energy Not Served.

Electricity area: The basic physical/geographical “building block” of the Sisyfos data set. Also called a node in the model. An electricity area is usually – but not necessarily – the same as a bidding zone. But in some cases, a bidding zone can be divided into several electricity areas.

EUE: Expected Unserved Energy. This is EENS corrected for the fact that whern the model predicts a certain number of MWh’s as EENS, it is usually not possible to brownout a demand of exactly this size, as brownouts usually happen in steps. Example: The model predicts EENS = 70 MW in a given hour. With brownout steps of 50 MW, it is necessary to brownout 2*50 MW. Thus EUE = 100 MWh.

KF21: Denmark’s Climate Status and Outlook 2021. https://ens.dk/en/our-services/projections-and-models/denmarks-energy-and-climate-outlook

Outage minutes: The number of minutes an average consumer experiences supply cuts. This is measured and reported directly by the distribution companies for grid adequacy. For Resource adequacy, the model first calculates EENS, the EUE, the outage minutes can be calculated af EUE/demand*8760*60.

PtX: Power-to-X, where electricity is used to produce hydrogen and (possibly) other fuels.

SOES: Security of electricity supply.

VOLL: **V**alue **o**f **L**ost **L**oad. An estimation in euro/MWh, of the maximum electricity price that customers are willing to pay to avoid an outage, cf. the electricity market regulation. I.e. the value/cost of not supplying electricity in monetary units per MWh of electricity.