Final report

1.1 Project details

Project title	NSON-DK
Project identification (program abbrev. and file)	64018-0032
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	Technical University of Denmark
Project partners	DTU Wind Energy (lead) DTU Management Ea Energy Analyses
CVR (central business register)	30 06 09 46
Date for submission	31. October 2020

1.2 Short description of project objective and results

1.2.1 English

NSON-DK is the Danish contribution to an international North Sea Offshore Network (NSON) research collaboration. The main objective of NSON-DK has been to study how the future massive offshore wind power and the associated offshore grid development is expected to affect the Danish power system in its transition towards a future sustainable energy system.

The main results of the NSON-DK project are:

- Establishment of optimal scenarios for offshore wind power and grid development towards 2050.
- Analysis of the impact of massive offshore wind power and offshore grid on market operation and balancing of power in North Sea countries.
- Analysis of the impact of massive offshore wind power and offshore grid on system adequacy of generation and transmission in the Danish power system.
- Analysis of impact of policy, regulation and market design on offshore wind power and grid development.
- Recommendations to stakeholders.

1.2.2 Danish

NSON-DK er det danske bidrag til et internationalt forskningssamarbejde om North Sea Offshore Network (NSON). Hovedformålet med NSON-DK har været at undersøge hvordan fremtidens massive udbygning med offshore vind omkring et offshore elnet in Nordsøen forventes at påvirke det danske elsystem i overgangen til fremtidens bæredygtige energisystemer.

De vigtigste resultater af NSON-DK er:

- Etablering af optimale scenearier for udviklingen af offshore vind og offshore net frem mod 2050
- Analyse af hvordan den massive udbygning af vindkraft og et offshore net påvirker elmarkedet og balanceringen af elsystemerne i Nordsø landene.
- Analyse af hvordan den massive udbygning af vindkraft og et offshore net påvirker tilstrækkeligheden af produktions- og netkapacitet i det danske elsystem.
- Analyse af påvirkningen af politiske beslutninger, regulering og markedsdesign på udbygningen af offshore vind og offshore net.
- Anbefalinger rettet mod interessenter.

1.3 Executive summary

NSON-DK is the Danish contribution to an international North Sea Offshore Network (NSON) research collaboration. The project has been executed in a collaboration between DTU Wind Energy, DTU Management and Ea Energy Analyses.

The main objective of NSON-DK has been to study how the future massive offshore wind power and the associated offshore grid development is expected to affect the Danish power system in its transition towards a future sustainable energy system.

NSON-DK has included the following research components

- Scenarios and investment studies which are performed to provide a common reference for the other work items in the project.
- Analysis of variability and uncertainty of offshore and onshore wind power.
- Market operation analyses to understand and quantify the potential impact of building a multiterminal offshore grid in the North Sea.
- Balancing and reserves analyses to understand how the increasing capacity of offshore wind power affects the need for balancing power and automatic reserves in the power system.
- System adequacy analyses to understand the impact of increasing shares of wind and solar power.
- Policy, regulation, and market design analyses to understand what is needed from the political side to support the development.
- Recommendations to stakeholders based on the findings in the above work items.
- Dissemination of the project results including project reports, conference papers, journal articles, webinars, and stakeholder meetings.

The overall conclusion from the research is to recommend the development of a multiterminal offshore grid in the North Sea which supports trade between countries as well as offshore connection of wind power instead of continuing the present practice connecting each offshore wind power connection point to the shore and supplement with interconnectors between countries.

This conclusion is substantiated by the following findings:

- The offshore grid will increase power trade across the North Sea countries.

- The offshore grid supports integration of more renewable generation which will be needed to implement the green transition.
- The investments in an offshore grid will be fully recovered by savings in operation costs.
- The spatially dense offshore wind power development does not increase the need for balancing compared to similar onshore wind and solar power development.
- The adequacy of the Danish power system is not reduced by the offshore grid.

1.4 Project objectives

1.4.1 NSON-DK objectives

NSON-DK is the Danish contribution to an international North Sea Offshore Network (NSON) research collaboration. The main objective of NSON-DK has been to study how the future massive offshore wind power and the associated offshore grid development is expected to affect the Danish power system in its transition towards a future sustainable energy system.

This objective has been detailed into five research questions in the work plan for the NSON-DK project. The five NSON-DK research questions are:

1. How will the offshore wind power development affect the variability and uncertainty of variable renewable generation in the Danish power system and neighbouring systems?
2. How will the offshore wind power and offshore grid development influence the electricity markets in future systems with large scale energy storage and coordination of the electricity system with other energy systems (mainly heat and transport)?
3. How will this increased variability and uncertainty from the offshore wind power development together with onshore renewable generation development influence the balancing and need for reserves in the Danish power system?
4. How will the scale and architecture of the offshore grid development influence the adequacy and security of supply in the Danish power system?
5. Which policy instruments should be applied to support an effective and cost-efficient transition of the Danish power system combining the offshore development with energy storage and coordination between energy systems?

1.4.2 Implementation of NSON-DK

Figure 1 provides and overview of the NSON-DK work including the following items:

- Scenarios and investment studies which are performed to provide a common reference for the other work items in the project.
- Variability and uncertainty analyses answering to research question 1.
- Market operation analyses answering to research question 2.
- Balancing and reserves analyses answering to research question 3.
- System adequacy analyses answering to research question 4.
- Policy, regulation, and market design analyses answering to research question 5.
- Recommendations to stakeholders based on the findings in the above work items.
- Dissemination of the project results including project reports, conference papers, journal articles, webinars, and stakeholder meetings.

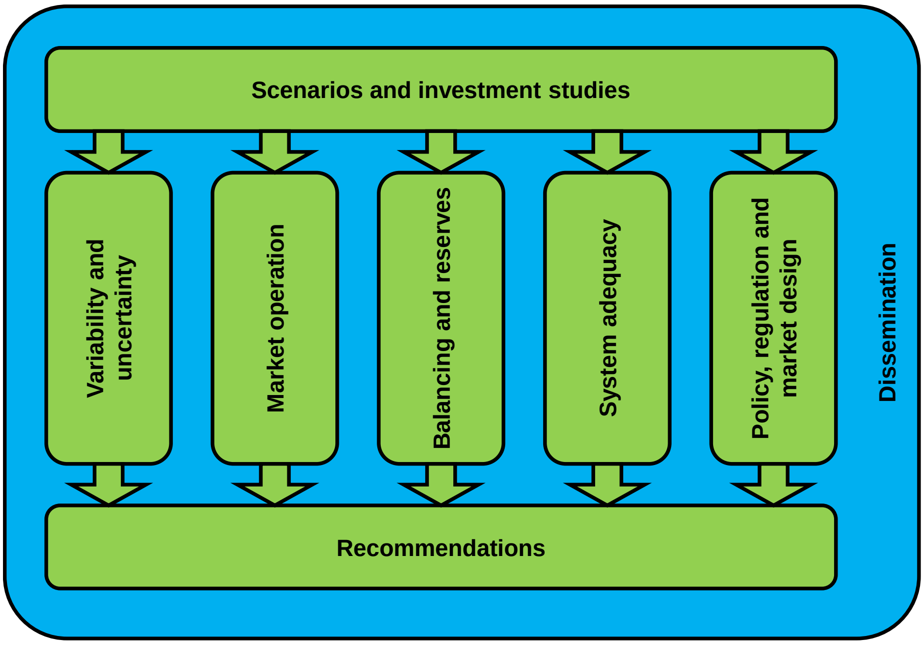

Figure 1. NSON-DK work items and main dependencies.

The implementation of NSON-DK is based on software tools which are used to answer the research questions and thereby meet the project objective. Figure 2 provides and overview of those tools, illustrating how the tools are connected and which are the major outputs from each tool.

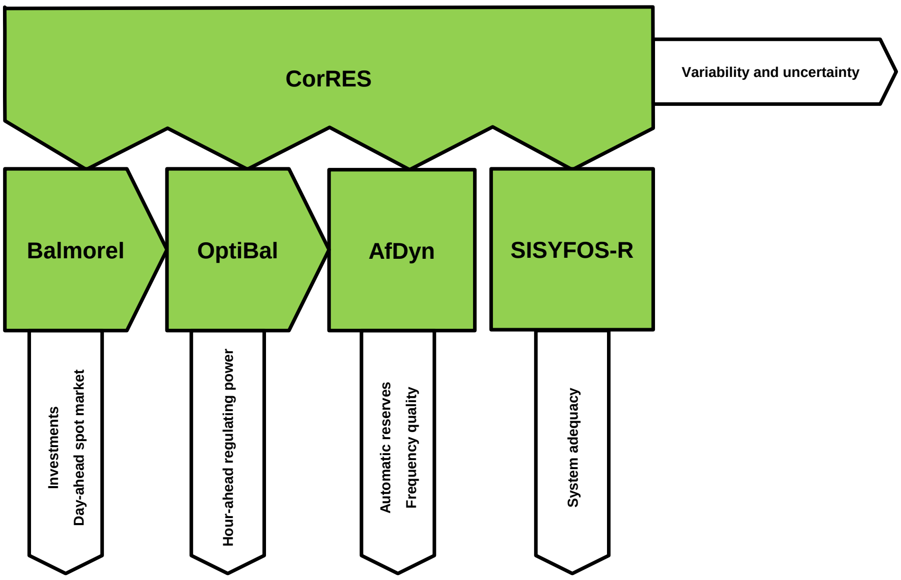

Figure 2. Tools applied in NSON-DK, how the tools are connected and what are the major outputs.

Alle the tools except OptiBal existed before NSON-DK, but NSON-DK has contributed to the (further) development of all the tools. The tools are:

- CorRES, which is developed by DTU Wind Energy. CorRES simulates time series of offshore and onshore wind and solar power in predefined power system regions. CorRES can simulate consistent time series of real time power and forecasts with different horizons, which is used to give different but consistent time series required as input to the other tools. The time series simulated with CorRES are also used directly in statistical analyses to provide the answers to research question 1 about variability and uncertainty.

- Balmorel, which is an open source tool used by DTU Management in NSON-DK. Balmorel is first used to generate optimal investments and then to simulate the day-ahead spot market using day-ahead RES generation time series. The results of the Balmorel spot market simulations are used to provide the answers to research question 2 and also contributes to answer research question 5.
- OptiBal is developed by DTU Wind Energy in collaboration with DTU Management. OptiBal is used to simulate the hour-ahead balancing using hour-ahead VRE generation forecasts from CorRES as well as the unit commitment and dispatch and technical data from Balmorel. Originally, the intension was to use the Simba (Simulation of Balancing) tool which was developed by the Danish TSO Energinet with assistance from DTU. However, Energinet has stopped the development of Simba, and it was not possible to develop further on this code. Instead, NSON-DK developed the more general OptiBal tool which uses mathematical optimization whereas Simba used a heuristic method to simulate the balancing. The main output from OptiBal is the hour-ahead balancing power plan which is used to answer the first half of research question 3 about the balancing.
- AfDyn is developed by DTU Wind Energy. AfDyn simulates the area and frequency control using a dynamic model. The inputs to AfDyn are the real time wind and solar power from CorRES and the power plan from OptiBal, which are used to calculate the real time imbalance. This real time imbalance must be handled by frequency restoration reserves (FRR) and frequency containment reserves (FCR). impact of the imbalance on the frequency quality. AfDyn is used to answer the second half of research question 3 about the need for reserves.
- SISYFOS was initially developed by Danish Energy Agency, but now SISYFOS-R is a joint development between the Danish Energy Agency and the NSON-DK partner Ea Energy Analyses. SISYFOS-R is used to analyse the system adequacy in the Danish power system. The results from SISYFOS-R simulations are used to answer research question 4.

1.4.3 Risks for NSON-DK

The project risks were identified in the work plan submitted with the proposal and have not been updated since then. The then identified risks are still valid and have been dealt with in the project.

Table 1 shows the project risks. The formulation of some of the risks is slightly modified to make them clearer in this final report than they were at the proposal stage. The impact on the project and the severity are also updated. Finally, the Mitigation is updated with the measures which have been applied to finalize the project.

Table 1. NSON-DK risks and implemented mitigation

Risk	**Impact**	**Severity**	**Mitigation**
Model development takes longer than expected (There was an unexpected need to develop optimization tools instead of using existing data and tools)	Project delay	medium	Several mitigations have been implemented: • Project has been extended • Master thesis have been supervised to contribute • Research assistants have been hired
Lack of data from European NSON partners for validation of generation pattern and un-	Less credible models	low	Data from ENTSO-E database were used instead to develop the PV forecast error model

certainty models			
Energinet will not develop SIMBA model to include real-time balancing and storage	Cannot include important balancing effects	medium	Developed own OptiBal
Conflicts between partners	Poor working climate	medium	No severe conflicts occurred
Insufficient and not timely input on offshore grids from European NSON partners	Insufficient scenarios	high	Used NSON-DK own optimization to create scenarios

1.4.4 Deviations and unexpected problems

The need to develop NSON-DK optimal scenarios was not realised in the original work plan. It was assumed that we could combine existing scenarios for offshore grid and wind power development, especially with inputs from the European NSON partners. Initial scenarios were developed based on public data – including contribution from European NSON partners. But it was difficult to get consistent scenarios from this puzzle, which could be used to analyse the feasibility of a future multiterminal grid in the North Sea.

We then got the opportunity to develop those scenarios using Balmorel, which delayed the project, but specifying consistent scenarios was prioritized because most of the other work items in the NSON-DK project had to use the scenarios.

As a result of this deviation, it was also approved that the original deliverables D2.1 on onshore energy system scenario and D2.2 on offshore development scenarios and RES generation were replaced by two editions of a D.2.1, both including onshore as well as offshore part of the scenario. The first edition then described the initial scenarios whereas the second deliverable described the optimal NSON-DK scenarios.

Another deviation – the possibility to develop on Energinets SIMBA software - was identified at the proposal stage, but the implemented mitigation was different from the original plan. SIMBA was not developed to work together with Balmorel, so instead of extending Simba with pre-processing and post-processing it became clear that it was better on the long-term to develop a new balancing tool and to the extent possible to validate that against Simba. This work started as a Master thesis but continued and was finalized by s a research assistant.

1.5 Project results and dissemination of results

In the following subsections, the project methodology and results are described for each of the work items in Figure 1. For the description of the R&D work items, the methodology is briefly introduced together with the associated results.

1.5.1 Scenarios and investment studies towards 2050

1.5.1.1 Approach

The NSON-DK scenarios have been developed to quantify the energy system investments in the North Sea region comprising Denmark (DK), Norway (NO), Great Britain (GB), Netherlands (NL), Belgium (BE) and Germany (DE). The North Sea region is shown on map in Figure 3.

Figure 3. North Sea region included in the NSON-DK scenarios.

The development of NSON-DK scenarios was divided into three stages: In the first stage, *initial scenarios* were specified to provide a starting point for the other R&D work items. In the second stage, *optimal investment scenarios* were developed to provide the final scenarios for the other R&D work items. Finally, *sector coupling scenarios* have been developed in the end of NSON-DK, but those scenarios were too late to be analysed in the other work items.

The *initial NSON-DK scenarios* were based on existing energy system scenarios in Nordic Energy Technology Perspectives (NETP) [1] and the European Wind Energy Association (EWEA) scenarios for offshore wind power by 2030 [2]. The initial NSON-DK scenarios are described in [3] and [4] and will not be further described here.

The *optimal investment scenarios* were then developed as the next stage. This was done to provide more detailed and transparent NSON-DK scenarios.

Two optimal scenarios were developed with the intension to enable analysis of the impact of the development of an integrated offshore grid in the North Sea:

The first optimal NSON-DK scenario is assuming "business as usual", i.e. that each project is developed independently, either as an offshore wind power cluster which is connected to an onshore market area by a dedicated transmission line or as an interconnector between two countries. Thus, the transmission system of each project has only two terminals. This scenario is referred to as the "project-based" NSON-DK scenario.

The second NSON-DK scenario is assuming that a multi-terminal offshore grid is developed to accommodate interconnection in the North Sea and grid connection of offshore wind power in one offshore grid in the North Sea. This scenario is referred to as the "offshore grid" NSON-DK scenario.

The Balmorel model and data from in NETP 2016 study [1] was used as a starting point for the optimal investment studies. The cost data was updated as follows: The Danish technology catalogue [5] was used as source for costs of generation including offshore and onshore wind and solar power. Assumed interest rate 4% was also taken from the Danish technology catalogue. Offshore hub and transmission costs are taken from the European NSON partners (Fraunhofer IWES, SINTEF Energy and ECN) published by Härtel et.al. [6].

The optimal investment simulation considered two stages: first towards 2030 and then further to 2050. The time window used to represent the analysed scenario years, i.e. 2030 and

2050, was reduced to eight weeks, to be able to obtain results in a reasonable amount of time. Subsequently, the time series were scaled so the total energy along a full year is preserved.

Since optimal investment simulations are very expensive in terms of computational power, 8 representative weeks spread over the year were selected and used in the optimization.

The *sector coupling scenarios* are a further development of the optimal investment scenarios adding coupling with heat and transport systems.

1.5.1.2 Results

The *optimal investment scenarios* were the main result as they were used in the other work items. The interconnections in NSON-DK optimized project-based scenario 2030 and 2050 are shown in Figure 4.

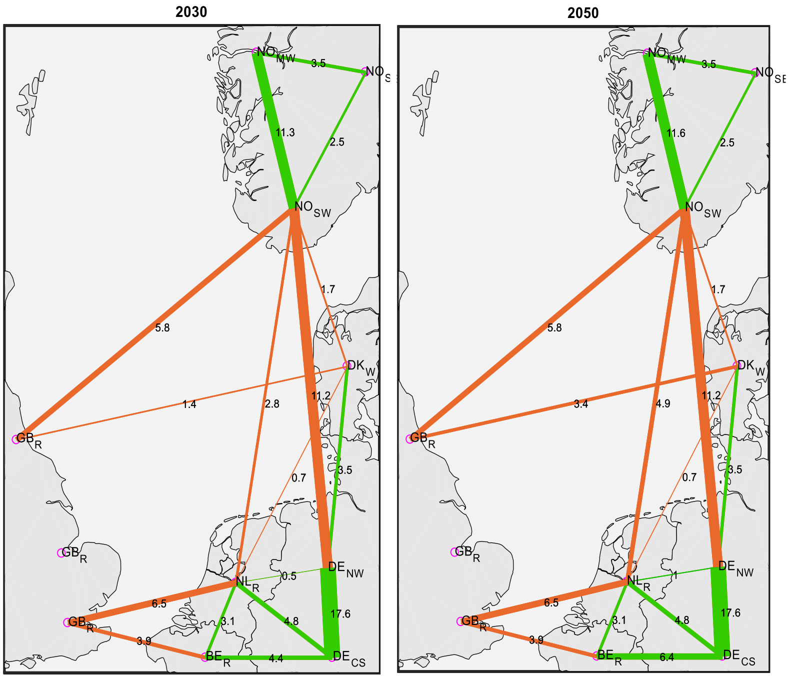

Figure 4. Interconnections in NSON-DK optimized project-based scenario 2030 and 2050.

The NSON-DK optimized offshore grid scenario 2030 and 2050 is shown in Figure 5. The value of considering expected future in the optimization is illustrated by the shared connection point, which is established towards 2030 as a 2 GW connection point with connections to 2 countries and further developed towards 2050 as a part of a 11 GW connection point with connections to 4 countries.

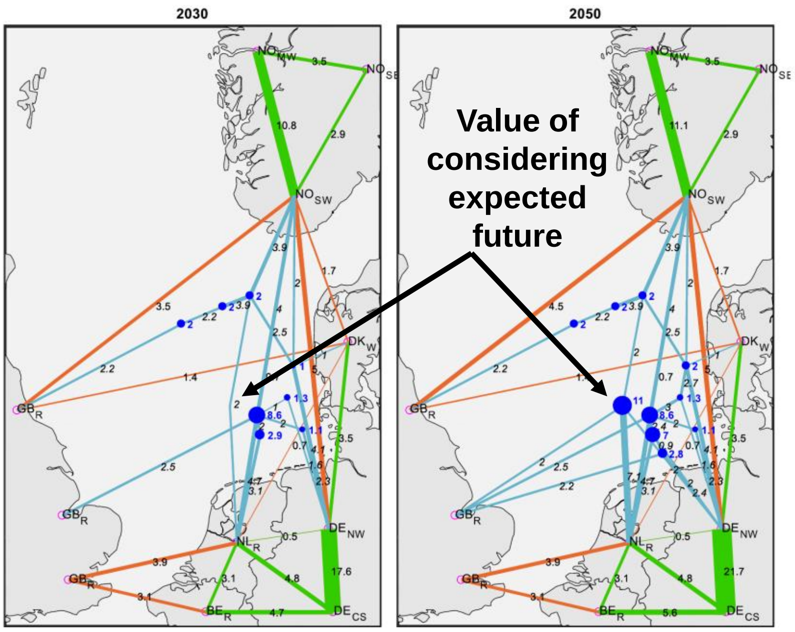

Figure 5. NSON-DK optimized offshore grid scenario 2030 and 2050.

The share of renewables and offshore wind in optimized NSON-DK scenarios are shown in Table 2.

Table 2. Share of renewables and offshore wind in optimized NSON-DK scenarios

Share of renewable capacity	**2020**	**2030**		**2050**	
	Approx	**Project based**	**Offshore grid**	**Project based**	**Offshore grid**
Share of renewables [%]	46	75	76	88	89
Offshore wind [GW]	22	64	69	92	102

The sector coupling scenarios do not include all potential sector couplings yet, but the preliminary results still show that sector coupling has a great impact on the optimal development of offshore wind power. The preliminary sector coupling results are shown in Table 3. It is remarkable that the included sector coupling implies that the optimal installed offshore capacity has increased with more than 50% reaching 158 GW by 2045.

Table 3. Share of renewables and offshore wind in preliminary NSON-DK sector coupling scenarios

Scenario year	**Electricity generation [TWh]**	**Share of Renewables [%]**	**Offshore wind [GW]**
2025	1284	58	25
2035	1537	94	126
2045	1717	96	158

The NSON-DK optimal investments are described further in the deliverable [7] and papers J. Gea-Bermúdez et al [8], [9] and M. Koivisto et al [10], [11]. Finally, scenarios including sector coupling are described by Gea-Bermúdez et al in [12] and Koivisto et al [13].

1.5.1.3 Conclusions

The main conclusions from the scenario work are:

- The integrated offshore grid progresses the offshore wind development, as the optimal offshore grid scenario results in ~10 GW more offshore wind by 2050 than the optimal project-based scenario.
- The offshore grid hubs allow for high OWPP investments with high capacity factors and supports an integrated transmission expansion.
- A combination of wind and solar PV is beneficial to the energy system because of the smoothening effect, i.e. that wind and solar power has low or even negative temporal correlation.
- Although the costs of offshore wind are higher than onshore, massive offshore wind power will be needed to implement the green transition because of limited land availability and social acceptance of onshore wind power development.
- The average electricity prices in 2050 are lower and more volatile than electricity prices in 2030. There is no significant difference between the price volatility in the project-based and the integrated offshore grid scenarios.
- The recent Danish policy regarding energy islands is not investigated explicitly in NSON-DK, but the large offshore hubs found in the integrated grid supports the feasibility of energy island solutions.
- Denmark is expected to be a significant electricity exporter by 2050, driven by good wind conditions and transmission connections to neighbouring countries.
- Distinguishing between investments up to 2030 and further to 2050, the NSON-DK optimal investment analysis without sector coupling places the majority of offshore wind power investments in 2030.
- Including sector coupling in the investment study increases massively the need for offshore wind, especially after 2030.

1.5.2 Variability and uncertainty

1.5.2.1 Approach

In the beginning of NSON-DK, CorRES was already very well developed for simulation of wind power with intra-hour resolution and of corresponding wind power forecasts. An example illustrating such simulations is shown in Figure 6, which was also included in the work plan for the NSON-DK proposal

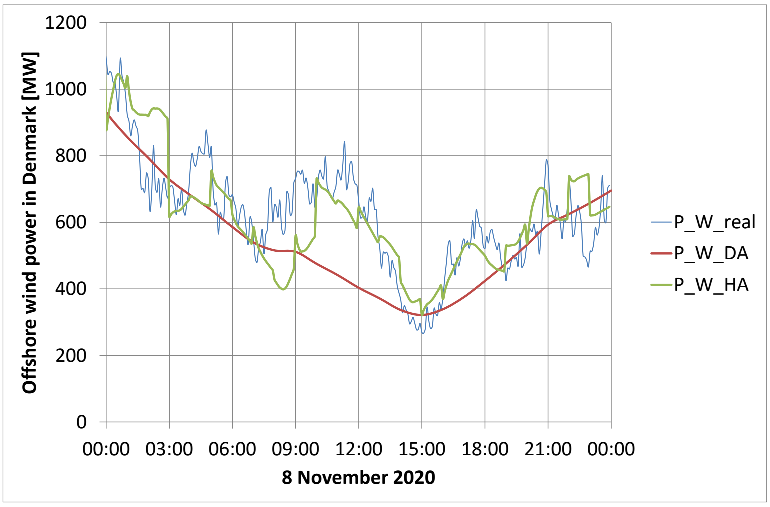

Figure 6. Example illustrating time series of real wind power (P_W_real), day-ahead (P_W_DA) and hour-ahead (P_W_HA) prognoses (simulated with DTUs CorWind software).

Those time series have been used in statistical analysis where the variability is quantified by the ramp rates of the real time power and the uncertainty is quantified by the forecast errors, calculated as the difference between the real and the forecasted value.

The NSON-DK project has supported further development of the CorRES tool. Two major contributions are:

- The development of a method for simulating solar power forecasts. CorRES was already able to simulate real time solar PV power, but forecast simulations were missing to have same capability for solar PV as for wind illustrated in Figure 6. The PV forecast simulations are described in papers by E. Nuno et al [14], [15].
- The development of a method to estimate missing data in the CorRES input database for wind power plants [16], [17]. CorRES simulations use wind turbine hub height, rotor diameter and power curve as input for each wind farm in the database, and for instance hub height can be estimated quite well from rotor diameter and / or nominal power.

NSON-DK also contributed to publish more general descriptions of the CorRES methodology in M. Koivisto et al [17], [18], [19].

Finally, CorRES is used in analysis of variability and uncertainty of variable renewable generation in M. Koivisto et al [20], [21], [22], [23], [13].

1.5.2.2 Results

CorRES simulations for the NSON-DK scenarios have answered research question 1 on how the offshore wind power development affects the variability and uncertainty of variable renewable generation in the Danish power system and neighbouring systems. The variability of variable generation can be quantified by ramp rates while uncertainties of variable generation are caused by the forecast errors.

As an example, Figure 7 shows the probability distributions of day-ahead forecast error in the western (DK1) and eastern (DK2) parts of the Danish power system. The first observation is that the distributions gets wider from 2020 through 2030 to 2050 because the installed capacity of renewables increase through the years. Another observation is that the 2030 and 2050 distributions for the offshore grid scenario are generally a little wider than the 2030 and 2050 distributions for the project-based scenario which is because the offshore grid scenario has higher offshore wind capacity than the project based scenario, see Table 2.

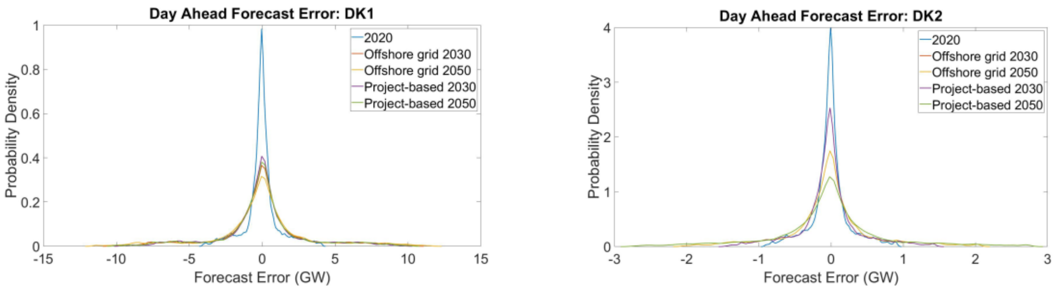

Figure 7. Day-ahead forecast errors in western (DK1) and eastern (DK2) Denmark [24].

Figure 8 shows the probability distributions of the hour-ahead forecast errors. The main observation here is that the hour-ahead distributions are more narrow that the day-ahead distributions which reflects that the hour-ahead forecast is more accurate than the day-ahead forecast.

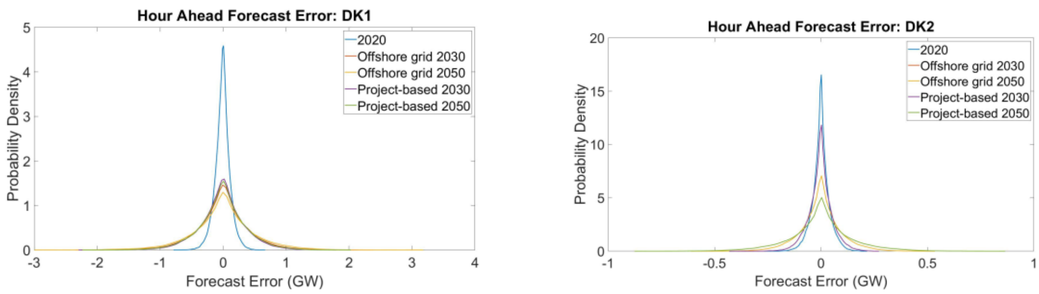

Figure 8. Hour-ahead forecast errors in western (DK1) and eastern (DK2) Denmark [24].

1.5.2.3 Conclusions

In summary, the main conclusions from the NSON-DK energy market analysis are:

- The offshore wind power development will increase the variability and uncertainty of variable renewable generation in the Danish power system.
- Combining wind and solar power reduces the variability and uncertainty compared to only developing with wind power.

1.5.3 Market operation

1.5.3.1 Approach

The NSON-DK research on market operation and balancing in the North Sea countries is based on the second stage, optimal investment scenarios. The idea has been to analyse the feasibility of the multiterminal offshore grid scenario comparing it to the two-terminal project connection scenario.

The latest version of Balmorel, BB4, was used to model the day-ahead spot market clearing of the full year. Day-ahead time series of wind and solar power were provided by CorRES simulations.

The Balmorel spot market simulations included unit commitment and dispatch as well as planned maintenance. The storage content, primarily of hydro power, is modelled in Balmorel rolling seasonal horizon mode which takes into account the opportunity costs of storage.

The NSON-DK energy market analysis is described in detail in the deliverable [25].

1.5.3.2 Results

Based on the NSON-DK optimal scenarios, the market operation analyses answering to research question 2 on how the offshore wind power and offshore grid development is expected to influence the electricity markets in future systems.

The Annual electricity balance between selected countries in focus are shown in Figure 9 for each of the NSON-DK optimal scenarios. It is noticed that Denmark becomes net exporter, mainly due to the wind and solar power development.

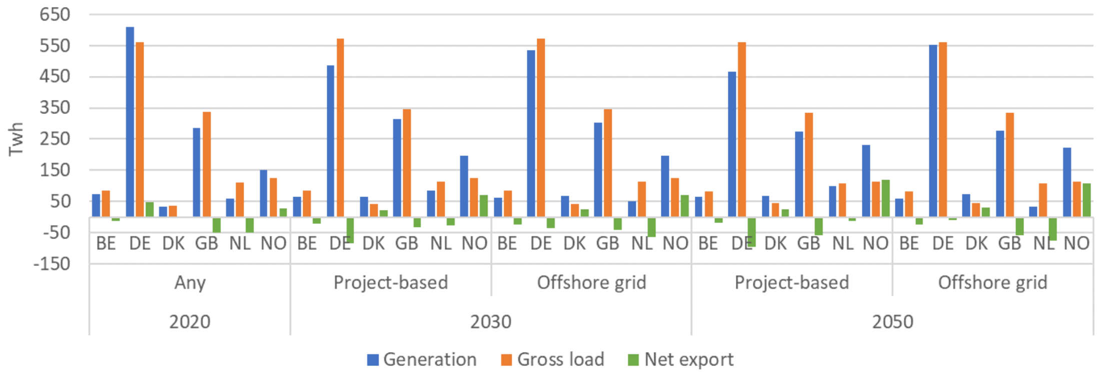

Figure 9. Annual electricity balance per scenario, country in focus, and energy scenario.

The share of renewable generation is shown in Table 4 for each of the optimized NSON-DK scenarios. The results show the strong increase in renewable shares over time and the impact of the offshore grid compared to the project-based scenario. It is seen that the offshore grid gives room for almost 10% (from 31% to 34% share) more offshore wind generation, but also reduces the onshore wind and solar generation. Still, the offshore grid scenario has the highest total share of renewables.

Table 4. Share of renewable generation in optimized NSON-DK scenarios

Share of renewable	**2020**	**2030**	**2050**

generation [%]	Approx	Project based	Offshore grid	Project based	Offshore grid
Offshore wind	7	23	25	31	34
Onshore wind	17	24	23	26	24
Solar PV	6	10	10	15	14
Total	30	57	58	71	73

The difference between costs of offshore grid and project-based scenarios is summarized in Table 5. It is seen that the investment costs (Capex) are significanly higher for the offshore grid, especially towards 2050, but the reduction in operation costs (Opex) is higher.

Table 5. Difference between costs of offshore grid and project-based scenarios

Year	Capex [M€/y]	Opex [M€/y]	Total [M€/y]
2030	213	-408	-195
2050	642	-660	-18

1.5.3.3 Conclusions

In summary, the main conclusions from the NSON-DK energy market analysis are:

- The integrated offshore grid scenario seems to be more cost-efficient than the individual project-based scenario. Thus, the added investment costs of the offshore grid (Capex) is fully compensated by the reduced operational costs (Opex) as shown in Table 5.
- The energy system in 2050 will be characterized by more trade and more efficient hydro power dispatch compared to today.
- The impact of the offshore grid scenario on the spot market operation is rather limited compared to the project-based scenario. However, this impact is expected to be higher for scenarios that include sector coupling because the sector coupling will allow a massive increase in the offshore wind development.

1.5.4 Balancing and reserves

1.5.4.1 Approach

The approach for the NSON-DK balancing analysis is illustrated in the Balancing Tool Chain Figure 10, which is a subset of the NSON-DK tool overview in Figure 2. The idea with the Balancing Tool Chain is to simulate each step of the balancing, starting with the spot market bidding already analysed in 1.5.3 and ending with the automatic frequency control in real time. The balancing and reserves activity is focusing on the hour-ahead balancing applying OptiBal and the area and frequency control applying AfDyn.

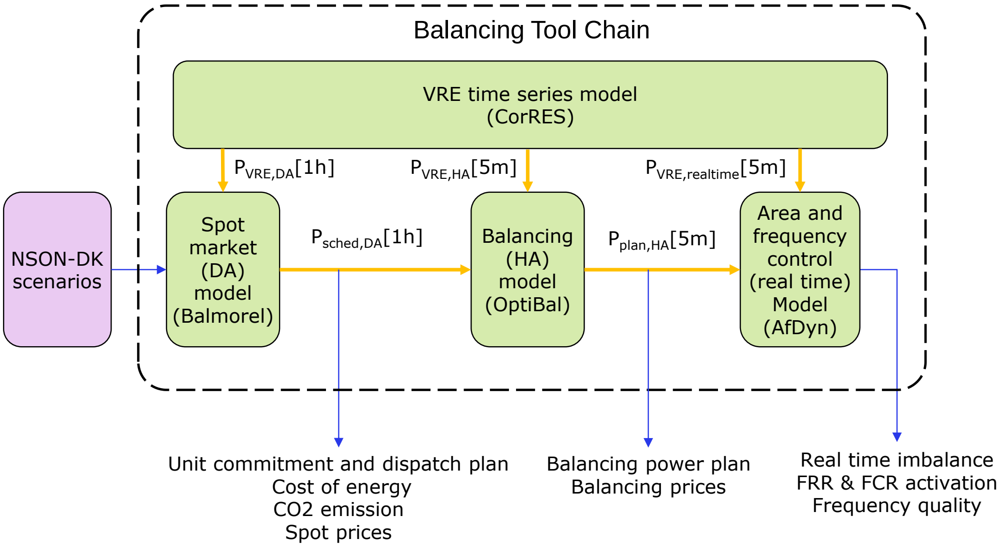

Figure 10. NSON-DK Balancing Tool Chain.

The OptiBal model receives as input the hour ahead wind forecast simulations in temporal resolution of 5 minutes from CorRES and the hourly generation schedule from Balmorel. The main purpose of this model is to calculate balancing power plan and associated prices. The balancing power plan is compensating for the imbalances caused by the forecast uncertainty which is reduced for the hour-ahead forecast (HA) compared to the day-ahead forecast behind the spot market dispatch.

The AfDyn model is a dynamic model simulating area and frequency control. Different models are used to simulate the Nordic and the Continental European synchronous areas to replicate the actual differences in the ways the frequency is controlled in those two synchronous areas. The frequency control in the Nordic synchronous area is based on normal and disturbance frequency containment reserves (FCR-N and FCR-D) and automatic frequency restoration reserves (aFRR). An overview block diagram of the corresponding model is shown in Figure 11.

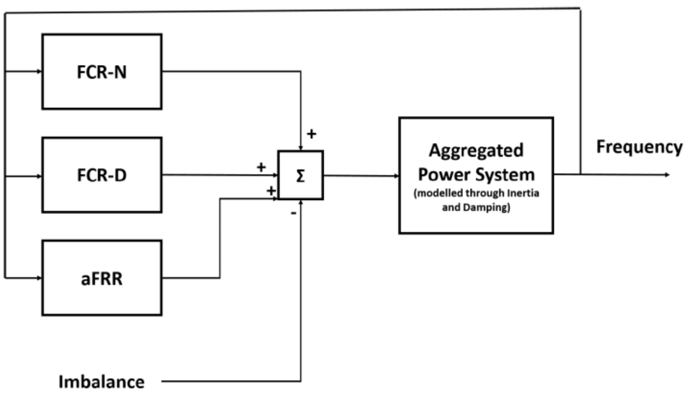

Figure 11. Area Control-Dynamic Model (AfDyn) applied for the Nordic synchronous area

The Continental European synchronous area also includes Load Frequency Control (LFC) in each country. This LFC is also modelled in that area.

The balancing analysis is described in detail in the deliverable P. Kanellas et al [24] and in the papers K. Das et al [26] and P. Kanellas et al [27].

1.5.4.2 Results

The balancing analysis are answering to research question 3 on how the increased variability and uncertainty from the offshore wind power development together with onshore renewable generation development influence the balancing and need for reserves in the Danish power system.

The input to OptiBal is the “imbalance before Optibal”, which is driven by the day-ahead forecast error relative to the updated hour-ahead forecast.

Figure 12 shows the distributions of imbalances before OptiBal in the Continental European and the Nordic synchronous systems. The imbalances in the synchronous systems are as expected higher than the day-ahead forecast errors in the Danish areas shown in Figure 7, but the trends are the same: the imbalance increases with increasing installed wind capacity, i.e. increases from 2020 through 2030 to 2050, and is higher for the offshore grid scenario than for the project based scenario.

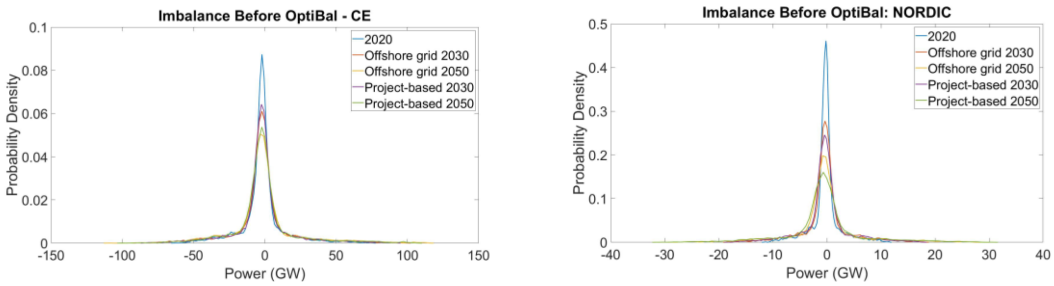

Figure 12. Distributions of imbalances before OptiBal in the Continental European synchronous system and in the Nordic synchronous system [24].

Figure 13 shows the Distributions of imbalances after OptiBal in the Continental European synchronous area and in the Nordic synchronous area. This imbalance is calculated using the real time wind power, so it is basically the same as the hour-ahead forecast error.

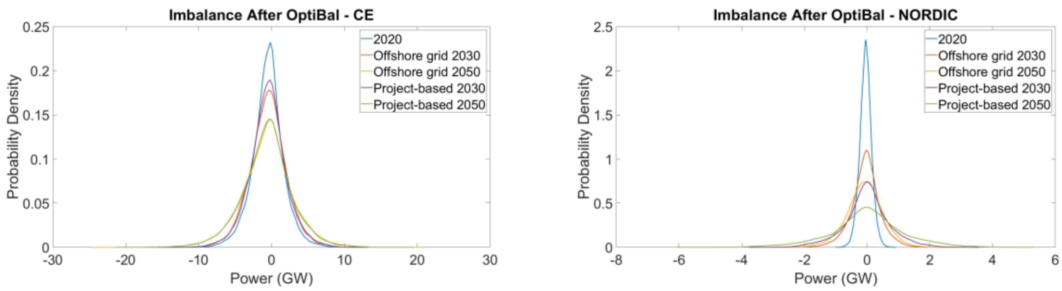

Figure 13. Distributions of imbalances after OptiBal in the Continental European synchronous area and in the Nordic synchronous area [24].

1.5.4.3 Conclusions

The main conclusions from the NSON-DK balancing analysis are:

- The power imbalances in all the North Sea countries increase substantially towards 2050, and therefore the operation in 2050 will require much higher volume of reserves. This increased imbalance is caused by the increased shares of offshore and onshore wind and solar power in 2050.
- The majority of the imbalances can be handled through slow manual balancing reserves based on hour ahead forecasts; nevertheless, much higher volume of automatic frequency restoration reserves will be required to handle the real-time imbalance and maintain the frequency quality.
- The need for automatic frequency restoration reserves varies significantly depending on the weather conditions, and therefore it is recommended to introduce probabilistic dimension of the automatic frequency restoration reserves to ensure more efficient utilization of those resources.
- The simulation results show that for the Continental Europe synchronous area, the offshore grid scenario has very similar impact on balancing of reserves as compared to the project-based scenario.
- On the other hand, real-time imbalance in Nordic synchronous area is much lower in case of offshore grid scenario as compared to project-based scenario, owing to more

wind power installation in Norway for project-based scenario as compared to offshore grid scenario.

- Unintended curtailed offshore wind power in the spot market has been found useful as up-regulation balancing reserve and other services like power2x, resulting in more value streams for wind power beyond spot market and also reducing requirement for reserves from other technologies.

1.5.5 System adequacy

1.5.5.1 Approach

The NSON-DK research on system adequacy in the Danish power system is based on the two second stage, optimal investment NSON-DK scenarios. Those are the project-based and the offshore grid scenarios described in 1.5.1.

The main assumptions behind the NSON-DK adequacy study are:

- The scope of the study is the Danish TSO 100+ kV transmission grid
- Import and export lines included
- The impact of a broader region is included, considering Baltics, Scandinavia, Northern Continental Europe, Great Britain
- Non-DK price regions are included as 'Copperplates'

The NSON-DK analysis of system adequacy in the Danish power system is done using the SISYFOS-R tool illustrated in Figure 14. SISYFOS-R uses Monte Carlo simulations to simulate outages of generators and transmission lines. This approach results in testing situations with many potential simultaneous outages (different from e.g. N-1). The stochastic approach allows simulation of outages through hundreds of years which ensures statistically robust results for the expected values of e.g. power outages (minutes per year) and energy not supplied (MWh/year).

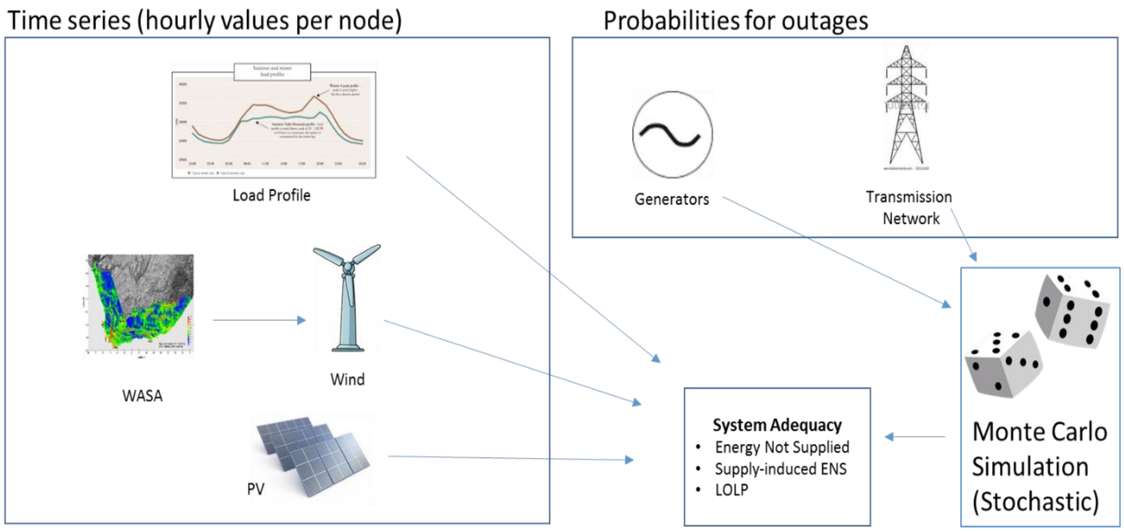

Figure 14. SISYFOS-R model for assessment of power supply adequacy

The load profiles are given as time series inputs, and so is the wind and solar power generation. Combining those input time series with the Monte Carlo simulation of outages, the system adequacy is analysed. The main output of this analysis is Energy Not Supplied (ENS). Another output is the Loss Of Load Probability (LOLP).

Besides the aggregated interconnection system in the NSON-DK scenarios, 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 15, which is the planned system for 2020.

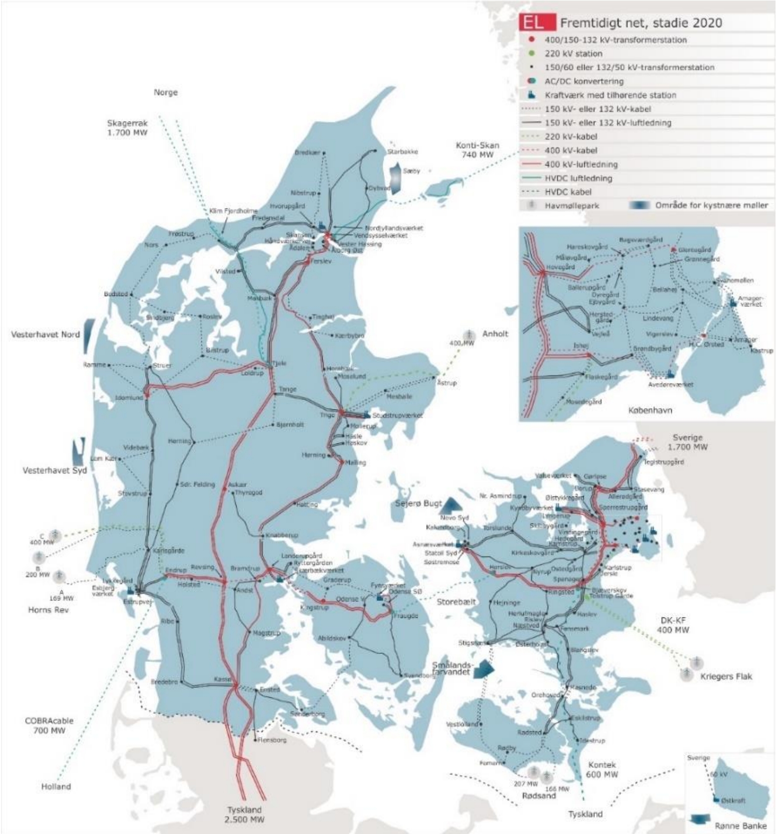

Figure 15. Planned Danish domestic transmission system, 2020. Danish Energy Agency/Energinet

The same grid is applied for the 2030 and 2050 studies. This 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.

1.5.5.2 Results

Based on the NSON-DK optimal scenarios, the adequacy analyses give answers to research question 4 on how the offshore wind power and offshore grid development is expected to influence the adequacy of the Danish power system.

Figure 16 shows the statistics for expected energy not supplied (ENS) in the Danish power system, calculated from SISYFOS-R runs with wind and solar power inputs from each of the optimal NSON-DK scenarios. The x-axis shows the number of years included in the outage simulations. This way, the figure verifies that the result is statistically solid with the applied 250 years. Using 250 years to ensure the best statistical significance, the difference between the ENS in the two scenarios is very small.

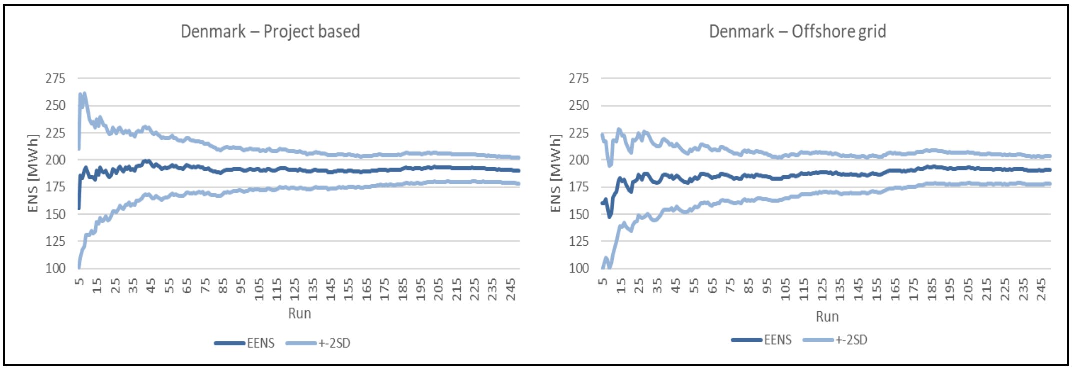

Figure 16. Statistics for expected energy not supplied (EENS) from SISYFOS-R runs with the two optimal NSON-DK scenarios

Figure 17 shows the expected outage minutes (power minutes) for the average consumer in Denmark when considering generation and transmission grid. This result shows how the power minutes decreases towards 2050 because the generation capacity is increased in the NSON-DK scenarios.

Figure 17. Expected outage minutes (power minutes) for the average consumer in Denmark when considering generation and transmission grid.

In order to show the importance to include the Danish transmisson grid in the analysis, Figure 18 shows the result calculated without the Danish transmission grid (Western and Eastern Denmark being copperplates). Comparing the low numbers for outage minutes in Figure 18 to the result in Figure 17 shows that the transmission grid is the main cause of outage minutes.

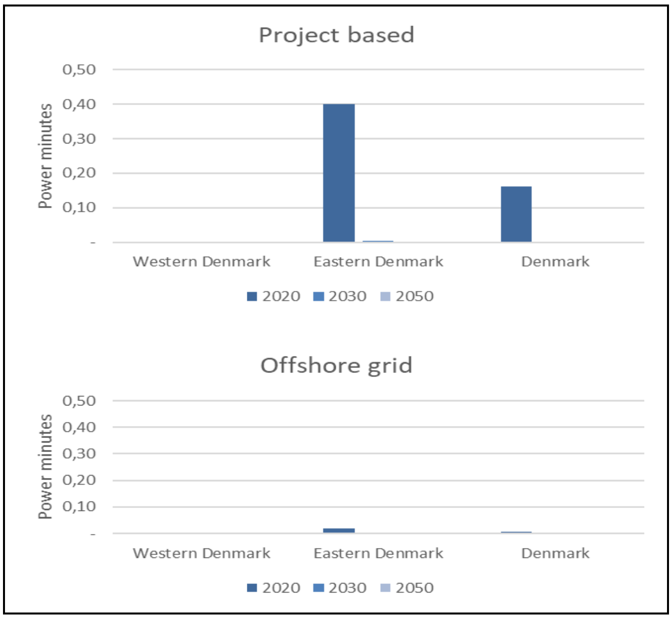

Figure 18. Power minutes without considering the domestic Danish transmission grid.

The approach and analyses of the NSON-DK system adequacy study is described in more detail in the deliverable [28].

1.5.5.3 Conclusions

The main conclusions from this study are:

- 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.
- Adequacy calculations indicate a downward trend in outage minutes towards 2050 for both Eastern and Western Denmark. On average in Denmark, adequacy numbers are improving from about 3.5 to 2.5 power outage minutes per year in both scenarios from 2020-50.
- 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 internal grid in Denmark is responsible for most of the unserved demand in Denmark.
- Simulation results and conclusions depend on the inputs. Thus, the thermal capacity to peak demand ratio increases towards 2050 in the NSON-DK scenarios, but decreases in Danish TSO calculations. As a result, the number of outage minutes are also lower in the NSON-DK analyses.

1.5.6 Policy, regulation and market design

1.5.6.1 Approach

The NSON-DK research on policy and market design consists of two parts: a policy brief and an analysis of market arrangements for offshore wind energy networks.

The policy brief identifies the relevant regulation towards the development of massive offshore wind as well as the hybrid integrated grid infrastructure in the North Sea. Furthermore, the policy brief addresses potential barriers related to the relevant regulation. Finally, possible solutions to overcoming these barriers are presented.

The aim of the market arrangement study was to explore different market arrangements for massive offshore wind generation in the North Sea that is at the same time internationally connected. The approach was an economic feasibility study for a concrete case, an offshore hub or energy island. The energy island connects 12 GW of offshore wind farms with interconnection capacity between Denmark, The Netherlands, and Germany. The complex energy system model Balmorel is used for optimisation.

1.5.6.2 Results

Based on the NSON-DK optimal scenarios, the policy, regulation and market design analyses answers to research question 5 on which policy instruments that should be applied to support an effective and cost-efficient transition of the Danish power system.

The framework conditions in different countries are summarized in Table 6. This summary shows that Germany has the most investment-friendly regulatory conditions.

Table 6. Framework conditions in different countries.

Regulatory framework condition	Good practices	Denmark	Belgium	Netherlands	Germany	Norway	UK
Connection	Super shallow cost recovery	+	o	o	+	o	o

cost							
Grid access tariff	Energy-based tariff / no access fee for producers	+	o	-	o	o	o
	No locational signal	+	+	+	+	-	-
Offshore grid friendly investment incentive	Limits the financial risk on CAPEX	+	+	+	+	+	+
	Full cost recovery of R&D spending	+	o	-	+	+	-
	Clear R&D incentive	-	o	-	+	+	o
	Incentive on OPEX /PBR	-	-	+	o	+	o
	Specifically supports CAPEX	-	o	-	+	-	+
	Limits CAPEX overspending	o	+	+	+	+	-

The NSON-DK policy brief is reported in the deliverable by L-L. Pade et al [29]. The NSON-DK analysis of market arrangements for offshore wind energy networks is reported in deliverable by L. Kitzing et al [30].

1.5.6.3 Conclusions

The main conclusions from the policy brief are:

- Policy measures to promote offshore grids should include an incentive package that provides clear incentives for R&D, full cost recovery of R&D spending, and that recognizes the effective investment risk in deployment by establishing risk-limiting financial measures, and by coupling profits to benefits through OPEX-related incentives.
- A super-shallow approach for grid connection cost allocation (allocating most of the costs to the TSO) is necessary to remove risks and reduce the complexity associated with the legal definition of the assets. It also reduces the financial risk for the wind farm developer.
- If grid access charges are applied to producers, they should contain an energy component only. Locational signals should be avoided, thereby enhancing the chances for the development of an offshore grid.
- Among the North Sea countries, Germany's regulatory framework is best suited to the development of an offshore grid, followed by Denmark and Norway. The regulatory framework of Belgium needs to be adjusted somewhat to support offshore grids, whereas there are several regulatory barriers in the Netherlands towards the development of an offshore grid. Finally, the regulatory framework of the UK is lacking behind with respect to supporting an offshore grid.

The main conclusions about offshore market arrangements are:

- For the offshore grid scenario to become real, there is great need for international cooperation.
- Our quantitative analyses confirm that integrated offshore solutions connecting different North Sea countries (Denmark, Germany and the Netherlands) will create total net societal benefits. The benefits and costs are, however, not equally shared across the countries.
- Cost-and-benefit sharing mechanisms and benefit transfers between countries will be needed to achieve a fair allocation and therewith adequate incentives for the realisation of interconnected offshore hubs in all countries.

- Market arrangements play an important role in this, as they reallocate surplus between different types of actors and between countries.
- Creating a separate offshore bidding zone can lead to a more efficient energy system set-up than sending the electricity to a home country market or granting Financial Transmission Rights to the offshore wind farm operators

1.5.7 Recommendations

The main recommendation from NSON-DK is to replace the precent "project based" practice connecting wind power plants directly to shore and building bilateral interconnectors with the development of an integrated offshore grid in the North Sea which supports trade between countries as well as offshore connection of wind power. This recommendation is substantiated by the following findings:

- The offshore grid will increase power trade across the North Sea countries.
- The offshore grid supports integration of more renewable generation which will be needed to implement the green transition.
- The investments in an offshore grid will be fully recovered by savings in operation costs.
- The spatially dense offshore wind power development does not increase the need for balancing compared to similar onshore wind and solar power development.
- The adequacy of the Danish power system is not reduced by the offshore grid.

Other recommendations from the NSON-DK are:

- It is important to ensure that the implementation of an offshore grid does not prevent the stepwise development of offshore wind power and country interconnection capacity.
- It is recommended to advance offshore grid in time as much as possible. Faster offshore development will not only support faster green transition but also be economically beneficial which is seen by the optimal investment studies.
- It is recommended to include balancing and frequency control in planning studies because massive shares of renewable generation will increase forecast errors and therefore more balancing capacity will be needed in the future.
- Long-term planning of the offshore grid is important to ensure that the right investment decisions are taken.
- A super-shallow approach for grid connection cost allocation (allocating most of the costs to the TSO) is recommended to remove risks and reduce the complexity associated with the legal definition of the assets.
- Coordination of the regulatory framework across the North Sea countries is required for a timely realisation of offshore grids.
- The existing EU framework will need to be revisited to optimally support the development of an offshore grid.
- Cost and benefit sharing mechanisms are needed to equalize costs for development of the offshore grid in some countries with benefits in other countries.
- Creation of offshore bidding zones should be considered to take full advantage of the offshore grid.

1.5.8 Impact of project

The project has already contributed to increased turnovers and employments in terms of commercial consultancy work and research projects.

The estimated impact of NSON-DK on the employment of the project partners is summarised in Table 7. The numbers show that Ea Energy Analyses and DTU Wind Energy expect those activities to grow in the future whereas DTU Management expects status quo.

Table 7. Estimated impact of NSON-DK on the employment of the project partners

Participant	Today	1-2 years	3-5 years
DTU Wind Energy	0.5	1.0	1.5
DTU Management	1	1	1
Ea Energy Analyses	0.3	1.2	1.5

The corresponding estimated impact of NSON-DK on the turnover of the project partners is summarised in Table 8. The reason why DTU Wind Energy turnover impact is not proportional to employment impact is that not only commercial work is included but also future expected research funded by EU, Nordic Energy Research and possible national funding.

Table 8. Estimated impact of NSON-DK on the turnover of the project partners [MDKK]

Participant	Today	1-2 years	3-5 years
DTU Wind Energy	0.8	1.2	1.8
DTU Management	-	-	-
Ea Energy Analyses	0.3	1.2	1.5

Typically, more than half of this work is in international projects, so minimum 50% of the increased turnover could be considered as export.

1.5.9 Dissemination of project results

The project results have been disseminated in written deliverables and in workshops, webinars and stakeholder meetings.

Table 9 lists the NSON-DK deliverables with the numbers in the References including links page 25 ff.

Table 9. NSON-DK deliverables

Number	Title	Ref
D2.1 Ed1	NSON-DK energy system scenarios - Edition 1	[3]
D2.1 Ed2	NSON-DK energy system scenarios - Edition 2	[7]
D3.1	NSON-DK Day-Ahead market operation analysis in the North Sea region towards 2050	[24]
D3.2	Balancing Tool Chain: Balancing and automatic control in North Sea Countries in 2020, 2030 and 2050	[24]
D4.1	System adequacy in alternative wind power scenarios	[28]
D5.1	NSON-DK Policy Brief	[29]
D5.2	Market arrangements for offshore wind energy networks	[30]
D6.1	Conclusions and Recommendations	[31]
D7.1	International expert workshop in Denmark	[32]
D7.2.1	Expert webinar (1/3) on scenario assumptions	[33]
D7.2.2	Expert webinar (2/3) on modelling VRE variability and uncertainty	[34]
D7.2.3	Expert webinar (3/3) on market modelling	[35]
D7.3.1	Stakeholder forum event (1/2)	[36]
D7.3.2	Stakeholder forum event (2/2)	[37]

The first expert webinar [33] on scenario assumptions took place 19. January 2017. This webinar included the following presentations:

- NSON_DK scenario building - Scenario for the onshore energy system. *T. Traber, M. Koivisto, DTU*
- NSON scenario development in the German NSON-DE project. *P. Härtel and D. Böttger, Fraunhofer IEE*
- Energinet.dk scenarios – towards 2030, 2035 and 2050. *A. Bavnhøj Hansen, Energinet*

The second expert webinar [34] on VRE generation patterns and uncertainties took place 29. May 2019. This webinar included the following presentations:

- CorRES tool: Modelling VRE variability and uncertainty. *M. Koivisto, DTU*
- Modelling wind power from reanalysis data: A review of datasets, methods and results. *Jon Olauson, KTH*
- Research activities of the Energy Economics and System Analysis group - Overview of models and selected study results. *Philipp Härtel, Fraunhofer IEE*
- Extending Stochastic UC&ED Beyond the Day Ahead Horizon. *Topi Rasku, VTT.*

The third expert webinar [35] on scenario assumptions took place 20. September 2019. This webinar included the following presentations:

- Adaptive aggregation in operational modelling of energy systems. *Topi Rasku, VTT*
- Overview of models and results on district heating. *S. Becker and Philipp Härtel, Fraunhofer IEE*
- Market modelling in NSON DK: Day Ahead simulations for balancing needs calculations. *J. G. Bermúdez and K. Das, DTU*
- Consumer centric electricity markets. Peer to Peer and community integration in energy markets. *T. Sousa, DTU*.

D7.1 and D7.3.1 were organized back-to-back in a side event of the Wind Europe Offshore conference in Copenhagen 28. November 2019. This side event attracted around 40 international participants.

The International expert workshop D7.1 [32] included the following 6 presentations from NSON-DK and the international NSON partners:

- NSON-DK energy systems scenarios. *Matti Koivisto, Technical University of Denmark*
- Market operation and balancing with future massive offshore wind power. *Kaushik Das, Technical University of Denmark*
- Impact of offshore grid on system adequacy of Danish power system. *Lars Bregnbæk, Ea Energy Analyses*
- Experiences and prospects of German NSON activities towards cost-efficient offshore wind connection and international integration. *Denis Mende, Fraunhofer IEE*
- Norwegian NSON project. *Harald Svendsen, SINTEF.*
- Market and regulatory issues. *Callum MacIver, University of Strathclyde.*

The first stakeholder forum event D7.3.1 [36] was organized as a panel session followed by a discussion between the panel and the room. The panel consisted of the following stakeholders:

- Rasmus Zink Sørensen, Danish Energy Agency
- Peter Godt-Larsen, North Sea Wind Power Hub / Energinet
- Finn Daugaard Madsen, Innovation Manager, Siemens Gamesa

Finally, the second stakeholder forum event D7.3.2 [37] was organized online 9. September 2020 to present the final conclusions and recommendations from the NSON-DK project. 6 NSON-DK experts presented the final conclusions and recommendations to 17 stakeholders from Danish Energy Authority, Danish Council on Climate Change, Energinet, Ørsted, Siemens Gamesa, DNV-GL and SupeGgrid Institute.

The project is also visible on several web-sites:

- NSON-DK project website [38]
- DTU Orbit: North Sea Offshore Network – Denmark [39]
- Ea Energy Analyses: North Sea Offshore Network. Wind and Solar Power [40]

1.6 Utilization of project results

The project has already created several opportunities for the partners:

- Ea Energy Analyses has applied knowledge and simulation tools developed in NSON-DK in several commercial projects including OFFSHORE WIND AND INFRASTRUCTURE funded by Ørsted og OFFSHORE WIND IN THE BALTIC SEA funded by the EU Commission. The Sysifos model which was further developed in NSON-DK, has also been applied in South Africa and Indonesia in collaboration with the Danish Energy Agency.
- DTU Wind Energy has applied knowledge developed in NSON-DK, including the further development of CorRES and the Balancing Tool Chain, in several commercial projects: First of all, DTU Wind Energy has signed a 5-year long-term contract with ENTSO-E to supply wind and solar power time series to ENTSO-E's Pan European Climate Database (PECD). ENTSO-E and the national TSO'er use PECD for the Ten Year Network Development Plans (TYNDP) and other transmission network planning. DTU Wind Energy has recently finalized a project for the Belgium TSO Elia analysing the development from 2.3 GW offshore wind power capacity in 2020 to 4.4 GW in 2026. Finally, DTU Wind Energi applies the results in other research projects and in education.
- DTU Management has applied some of the knowledge from NSON-DK in two commercial consultancy projects in the context of the North Seas Energy Cooperation and the North Sea Wind Power Hub consortium. Both projects deal with the regulatory framework and necessary political collaboration to create an offshore grid infrastructure.

The project is expected to create additional opportunities for the partners in the future:

- Ea Energy Analyses expect an increased consultancy activity regarding offshore wind power and grid in the future. Ea Energy Analyses has in a consortium won a large framework contract on "Consultancy Services Wanted for North Sea Wind Power Hub" for Energinet, Tennet og Gasunnie. This project is intended to analyse how to develop an economical, efficient and coordinated utilisation of the wind resources in the North Sea.
- DTU Wind Energy expects to continue the collaboration with ENTSO-E, also after the contract expires in October 2023. Also, the collaboration with Elia is expected to continue with an updated analyses in 2022. With those strong references in addition to NSON-DK, DTU Wind Energy also expects consultancy contracts in other countries and participation in more research projects in the area.
- DTU Management expects future research and consultancy activities to support the international collaboration between policy makers, market actors and to idenfity the best regulatory framework and market conditions for offshore development.

1.7 Project conclusion and perspective

The main conclusion from NSON-DK is also forming the main recommendation: It is recommended to develop a multiterminal offshore grid in the North Sea which supports trade between countries as well as offshore connection of wind power instead of continuing the present practice connecting each offshore wind power connection point to the shore and supplement with interconnectors between countries.

This conclusion is substantiated by the following findings:

- The offshore grid will increase power trade across the North Sea countries.
- The offshore grid supports integration of more renewable generation which will be needed to implement the green transition.

- The investments in an offshore grid will be fully recovered by savings in operation costs.
- The spatially dense offshore wind power development does not increase the need for balancing compared to similar onshore wind and solar power development.
- The adequacy of the Danish power system is not reduced by the offshore grid.

Other recommendations from the NSON-DK are:

- It is important to ensure that the implementation of an offshore grid does not prevent the stepwise development of offshore wind power and country interconnection capacity.
- It is recommended to advance offshore grid in time as much as possible. Faster offshore development will not only support faster green transition but also be economically beneficial which is seen by the optimal investment studies.
- It is recommended to include balancing and frequency control in planning studies because massive shares of renewable generation will increase forecast errors and therefore more balancing capacity will be needed in the future.
- Long-term planning of the offshore grid is important to ensure that the right investment decisions are taken.
- A super-shallow approach for grid connection cost allocation (allocating most of the costs to the TSO) is recommended to remove risks and reduce the complexity associated with the legal definition of the assets.
- Coordination of the regulatory framework across the North Sea countries is required for a timely realisation of offshore grids.
- The existing EU framework will need to be revisited to optimally support the development of an offshore grid.
- Cost and benefit sharing mechanisms are needed to equalize costs for development of the offshore grid in some countries with benefits in other countries.
- Creation of offshore bidding zones should be considered to take full advantage of the offshore grid.

With those conclusions in mind, the perspective of building offshore wind power hubs in multilateral collaborations is substantiated by the NSON-DK project.

Another observation is that the future development of sector coupling technologies is expected to have a significant impact on the optimal design of the offshore grid and the onshore systems, and it is therefore important to maintain and develop system studies in the future which combine the impact of offshore development, CO_2 reducing technologies and sector coupling updated with data for the latest energy technology development.

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