Technical University of Denmark

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Das, Kaushik; Koivisto, Matti Juhani; Sørensen, Poul Ejnar; Gea-Bermudez, Juan

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Balancing Challenges for Future North Sea Offshore Network

Kaushik Das, Matti Koivisto, Poul Sørensen
Department of Wind Energy
Technical University of Denmark
Roskilde, Denmark
kdas@dtu.dk, mkoi@dtu.dk, posq@dtu.dk

Juan Gea-Bermúdez
Department of Management Engineering
Technical University of Denmark
Kgs. Lyngby, Denmark
jgeab@dtu.dk

***Abstract*— In future, large volume of offshore wind power developments can be envisaged in North Sea. Large share of renewables infers large fluctuations. Also, large share of renewables infers large forecast error. These forecast errors and fluctuations create balancing challenges in the power system. A model tool chain encompassing market modelling, forecast simulations, intra-hour balancing, area control modelling is discussed in this paper. Case study for scenario of 2035 and 2050 are performed using this tool chain. These case studies are used to demonstrate the balancing challenges in future Danish power system. Finally, the research questions required to be answered regarding balancing of future power system with large offshore development in North Sea are pointed out.**

***Index Terms*—balancing, forecast error, modelling, offshore wind power, reserve adequacy, uncertainty, wind power**

I. Introduction

Integration of renewable energy sources in power systems has been increasing over last decade mainly to meet environmental needs, energy security concerns and sustainable development goals. At the same time, reducing prices of wind and PV technology makes it further conducive for installation and grid integration. Among the renewables, wind power is one of the fastest growing generation sources. Offshore wind power has been developing quite a lot lately. For example, 16.8 GW (15.6 GW in EU) of wind power was installed in Europe in 2017 making the net capacity 169 GW. Out of 15.6 GW, 12.5 GW installations were onshore, and 3.1 GW were offshore installations [1]. Majority of these offshore installations have been in North Sea for high wind resource availability and shallow water depth. All the predictions suggest that in future there will be massive offshore installation to such an extent that there are intentions for developing offshore artificial island for hosting substations and other electrical equipment like transformers, switch gear etc.

Future massive offshore wind power and the associated offshore grid development in North Sea pose many challenges towards power system balancing in North Sea neighboring countries. The locations of the offshore wind power plants are expected to be concentrated in relatively small areas where wind conditions are favorable. This spatial concentration of offshore wind power can cause high power fluctuations. The power variations in power systems are generally handled through prognoses of wind power at different time scales. Power is generally traded on the day-ahead spot-market based on the day-ahead prognoses, whereas the hour-ahead prognosis is the basis for the hour-ahead balancing performed by TSOs. The difference between the day-ahead and hour-ahead prognoses quantifies the need for balancing reserves to perform this hour-ahead balancing, while the difference between the real time wind power and the hour-ahead prognoses quantifies the subsequent need for real time balancing reserves to avoid deviations from the planned power exchange with neighboring countries. Real time imbalances are handled by automatic and manual frequency reserves. One of the major challenge involves estimation of adequacy of reserves to handle the imbalances caused by forecast error. There might be higher reserve requirements in those future operational scenarios. Availability of such high reserves all the time can be an expensive solution. There might be other market-based solutions to activate real-time markets closer to time of operation when forecast error is low. However, to perform these studies new simulation tools are required which encompasses different simulation capabilities starting from simulation of forecast errors, spot market-based unit commitment, inter-hour balancing, real-time balancing etc.

There are certain tools and models available for estimating reserve requirements. ERCOT's KEMA Renewable Market Integration Tool (KERMIT) [2] allows dynamic simulations for future scenarios at second resolutions for up to 24 hours considering events such as generator trips, sudden load rejection, and volatile renewable resource (wind, solar) ramping events. Advance Dispatching [3] is jointly developed by Terna and CESI and currently in operation at the National Control Centre in Rome for adequacy analysis of the Italian power system, supporting Control Room Operators in the real-time dispatching phase. It analyzes the impact of future state of the power system based on expected weather and load and to make considerations on the adequacy through scheduled

Unit Commitment. Balancing market model [4] implements balancing markets in the northern European power system to procure reserves in the balancing areas. DTU Wind Energy has developed a balancing model tool chain that encompasses day-ahead market operation modelling, intra-hour balancing model and manual and automatic reserve activation for Danish power system. This model tool chain can assess the adequacy of reserves for handling imbalances due to forecast uncertainties for renewable generations and loads as well as imbalances arising for different time resolutions in day-ahead market bidding and hour-ahead balancing. Detailed comparison of these tools can be found in [5].

This paper describes the functionality of above mentioned balancing model tool chain. The balancing challenges that might occur in future Danish power systems with large volume of wind power development in North Sea region is also analyzed. Balancing challenges are exemplified through a case study of a typical week in Danish power using future northern European scenario of 2035 and 2050.

II. Balancing Model Tool Chain

A balancing model tool chain as shown in **Figure 1** is developed to study the impact of variability and forecast error of renewable generations on Danish power network. This model tool chain accounts for market trading as well as control practices at different points of time: The power is first traded on the spot market based on day-ahead prognoses, then the power is balanced based on hour-ahead prognoses using the regulating power market like NOIS, and finally the power is balanced using contro

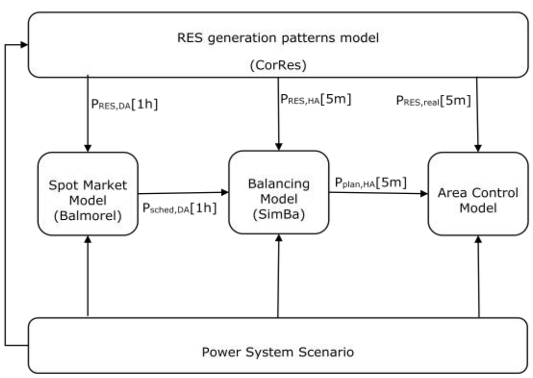

Figure 1 Balancing Model Tool Chain

Functional requirements for each of the blocks in Figure 1 is described briefly below.

A. Power System Scenario

The scenario used in this paper is the result of an investment optimization performed for the energy system of the North Sea countries, i.e. Denmark, Norway, Great Britain, Germany, Belgium and Netherlands. The tool used was the Balmorel energy system model [6], and with this, electricity generation and transmission investments towards 2050 were optimized in these countries.

The starting point for the optimization was Nordic Energy Technology Perspectives (NETP) 2016 [7], although several aspects were updated. The most significant modifications with respect to NETP 2016 were introducing the possibility to invest in a meshed grid in the North Sea and build hub-connected offshore wind power plants (OWPPs), and the updated cost development assumption of variable renewable energy (VRE) technologies - solar PV, wind onshore, and wind offshore based on [8]. Also, the intertemporal optimisation available in Balmorel [6] was used; it takes into account the expected development in 2050 when optimising the 2035 scenario year.

The main output of this optimization process are two scenarios: The "Radial Case" and the "Meshed case". The difference between them is that in the "Radial Case", the meshed grid in the North Sea and hub-connected OWPPs were not allowed. For the purpose of this paper, we have purely used the "Radial Case". Further details about the scenario modelling can be found in [9] (note: some input data was changed for the scenario shown in this paper; thus the resulting scenario is different compared to [9]).

The Radial Case scenario resulted in an important penetration of VRE into the electricity system. In this scenario, by 2035 around 67% of the electricity generation in the North Sea countries was produced by VRE, and by 2050, 74%. This massive penetration was possible thanks to considerable investments in transmission, which played an important role in balancing the energy system. The transmission investments by the years 2035 (left) and accumulated investments by 2050 (right) for the scenario can be seen in **Figure 2**. It is important to highlight that the figure does not include the exogeneous lines (existing and expected short-term plans) by those years, e.g. the cobra cable between DK and NL. It only shows the additional investments found as optimal.

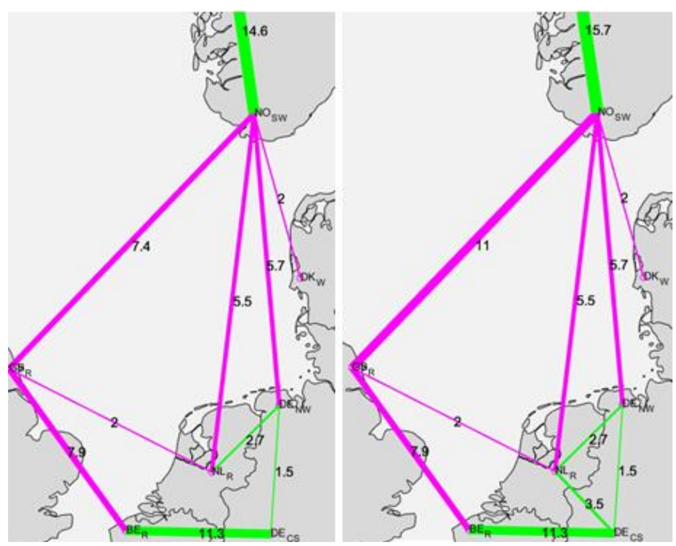

Figure 2. Endogenous transmission investments in 2035 (left) and accumulated endogenous transmission investments by 2050 (right) in GW. On-land lines are drawn in green, and HVDC offshore lines in magenta.

Table 1. VRE annual production and demand

	VRE total (TWh)		Consumption (TWh)	
	2035	**2050**	**2035**	**2050**
BE	52	50	85	83
DE	310	305	574	562
DK	50	60	43	44
GB	259	285	345	334
NL	101	119	113	109
NO	54	68	125	114

Curtailment increases from 2035 to 2050 significantly, which can reduce VRE energy generation.

In this context, already by 2035, Denmark was found to become a net exporter of VRE, producing 18% more energy than its electricity demand. Table 1 shows the VRE generation compared to the electricity consumption of each country for the years 2035 and 2050.

The intertemporal optimisation in Balmorel contributed in having a very large VRE share already by 2035, as expected CO2 emission costs in 2050 were taken into account when optimising 2035 investments. In addition to DK, NL and NO are expected to become significant electricity exporters, exporting also to DE to counter the significant decommissioning of fossil and nuclear generation capacity.

This level of penetration increases the importance of forecast errors and the need for balancing power. That is the reason why the balancing challenges of such an energy system will be studied in this paper.

B. RES generation pattern models - CorRES

The tool covering the simulations of both wind and solar PV generation time series is called CorRES. The capabilities of the CorRES tool for simulating large-scale variable renewable energy (VRE) generation has been shown in [10]. CorWind, which is the wind simulation part of CorRES, is a highly developed tool to simulate consistent and correlated wind power generation patterns and uncertainties for single wind turbines or aggregated over wind farms or power system areas as specified by the model user. In addition to wind, CorRES includes solar PV simulation capabilities.

C. Spot Market Model - Balmorel

Modelling of spot market is developed in Balmorel. Balmorel is a model for analysing the energy system with emphasis on electricity and heat; and used in several countries (e.g. energy companies and TSOs). The Balmorel model is coded in the GAMS model language, and the source code is open source. Balmorel is a multi-period model with flexible time and area resolution. Balmorel is used for performing economic dispatch and unit commitment of the generating units using the day-ahead renewable forecasts obtained from CorRes.

Generation must match consumption in the power market. This balancing is performed through bidding in day ahead market based on renewable generation forecast and load forecast in Balmorel.

D. Intra-hour Balancing Model – SimBa

SimBa is developed by Energinet in cooperation with DTU as a tool to simulate the balancing of the Danish power system [11]. The purpose of SimBa is to model intra-hour balancing of Danish power system. In this tool chain, SimBa is used to estimate the volume and cost of reserves required for balancing. This tool provides guidance on assessing whether enough reserve providing generation sources are available for future Danish power system.

Based on the bids in spot market (modelled in Balmorel), market price for each hour in the day of operation is generated. Based on the day-ahead schedules of the generators, available regulating reserves (or online available capacity) are estimated; if the generators are willing to participate for balancing. These participants constitute a list called NOIS list (a Nordic market place for regulating power). TSO can activate regulating reserves from this list according to certain rules. It should be noted that the bid activation need not to be within one of the two Danish price areas; it could be anywhere in the whole Nord Pool Spot Market area.

The input to SimBa are time series of energy and prices for productions, consumptions and exchanges at hourly resolution. SimBa transforms these time series into smaller time resolutions through splining to simulate real-time operational power schedules. Power schedules for consumption are generated by smoothening the input time series. Power schedules for import and export exchanges are generated respecting ramping conditions. Power schedules for conventional generators are obtained by ramping between last hourly values to next hourly values while respecting the ramping characteristics of the concerned generating unit types. Power schedules for renewable generations are generated based on forecasts obtained from CorRes.

Based on these power schedules, system imbalance prior to the operating hour is generated. This imbalance is to be balanced by activating regulating power based on a merit order list of upward and downward available capacities. This merit order list simulates the NOIS market. Activation of regulating reserves are done while obeying the rules of activation.

E. Area Control Model - Frequency Restoration and Frequency Containment Process

The output of SimBa constitutes residual imbalance that need to be balanced using frequency restoration process (FRP) and frequency containment process (FCP). The main purpose of FCP is to contain the frequency within certain pre-decided bands following a large imbalance (generally caused by a large disturbance). Danish power system is divided into 2 separate power systems western Denmark (DK-1) and eastern Denmark (DK-2) connected to Continental Europe (CE) synchronous area and Nordic synchronous area respectively. These two areas have different requirements and operating principles for handling real-time imbalances. FCP is automatic, governor-based control in DK-1, however, FCP in DK-2 is modelled separately for normal operation (FCR-N) and disturbance (FCR-D). Detailed discussion on different types of reserves in DK-2 and Nordic power system can be found in [13]. Since DK-1 is connected to CE, FRP is handled using an automatic load frequency controller (LFC). Frequency restoration reserves (FRR) deployed by FRP are dimensioned based on the guidelines as given in ENTSO-E Network codes on FRR dimensioning [12]. The purpose of LFC is to restore frequency and maintain the tie-line power flow commitment.

However, it should be noted that the main purpose of these automatic reserves is to handle large unforeseen disturbances such disconnection of a large generator. In case, these reserves are used by the power system to mitigate imbalances caused due to forecast error, the security of the power system is compromised and therefore should be avoided [14],[15],[16].

III. CASE STUDY

In the presented case studies, two typical weeks are simulated for scenarios in 2035 and 2050. Figure 3 shows onshore and offshore wind power generations, solar power generations and consumption based on the unit commitment output using Balmorel. It can be observed that although consumption remains similar in 2035 and 2050 scenarios, increase in offshore wind and solar power is substantial. High share of VRE implies larger fluctuations. Therefore, it is particularly challenging to operate and balance the power system when the VRE generations are very high.

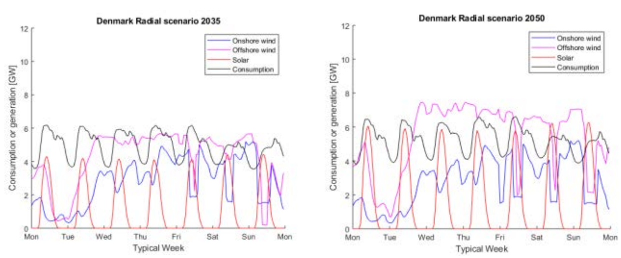

Figure 3 Generation and consumption in a typical week

Consequently, total VRE generation is much more than the consumption as can be seen from Figure 4. Figure 4 also shows residual generation i.e. excess VRE generation than consumption in Denmark. This excess generation will be transmitted to neighboring regions, when there is requirement in these regions.

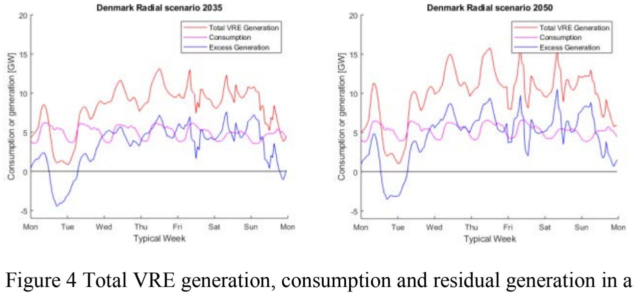

Figure 4 Total VRE generation, consumption and residual generation in a typical week simulated for 2035 and 2050

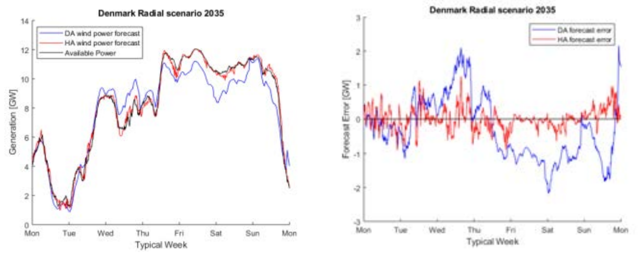

Figure 5 Forecast vs. available wind power in a typical week simulated for 2035

It should be noted that in case the total demand in Denmark and neighboring regions is still less than generations, then the VRE generations are curtailed. This can be comprehended better looking at Figure 5 and Figure 6. If offshore wind in Figure 3 is observed closely around Friday and Saturday, curtailment can be observed. This is more evident when day-ahead forecast of wind power is observed in Figure 5 and Figure 6. This day-ahead forecast is used for unit commitment and there is no reduction of wind power can be observed in day-ahead forecast in Figure 5 and Figure 6.

Figure 5 and Figure 6 also show hour-ahead forecast and real-time available power for 2035 and 2050 scenarios respectively. Computing the difference between day-ahead and real-time available power gives the day-ahead forecast error. Similarly, hour-ahead forecast error is computed as difference between hour-ahead forecast and real-time available power. Figure 5 and Figure 6 show hour-ahead forecast error is typically less than day-ahead forecast error. This knowledge is used by TSO to balance the imbalance caused due to day-ahead forecast error.

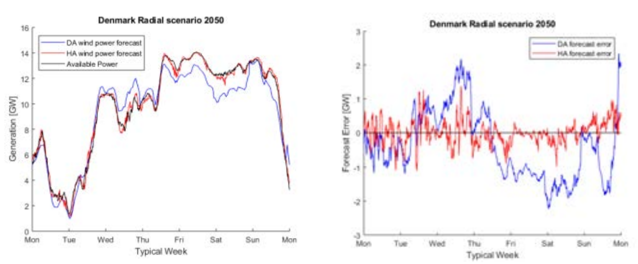

Figure 6 Forecast vs. available wind power in a typical week simulated for 2050

Another important point should be noted that there are two fundamental reasons for imbalances. Unit commitment is performed with hourly resolution. Therefore, an inherent imbalance is caused during hourly shifts due to ramping of the generators to change setpoints or starting and shutting down of the generators. Another component of the imbalance is day-ahead forecast error for generators and loads.

These imbalances are generally handled by slow manual reserves from the NOIS list as modelled by intra-hour balancing in SimBa and mentioned in previous section. However, hour-ahead forecast error is used for balancing. The difference between day-ahead wind power forecast error and hour-ahead wind power forecast error as shown in Figure 7 can be used to estimate the manual reserves required to handle the imbalance caused by day-ahead wind power forecast error.

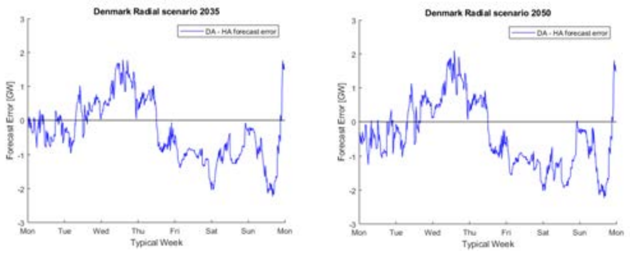

Figure 7 Difference between day-ahead and hour-ahead wind power forecast error

It can be seen from Figure 7 that the reserve requirements in future scenario to mitigate the imbalance as simulated in this typical week can be as high as 2 GW. However, it should be noted that this value can be reduced if better forecasts are available.

To have general idea about the reserve requirements, wind power forecast errors are simulated whole year. Probability density functions of the wind power forecast errors are plotted in Figure 8. It shows that day-ahead wind power forecast error can be as high as 4 GW. Hour-ahead wind power forecast error is statistically lower than day-ahead forecast error, but the tail can still be as high as 1 GW in 2035 and around 1.5 GW in 2050. This is particularly important since this error must be handled by automatic FRR and FCR as modelled by area control error as discussed in previous section.

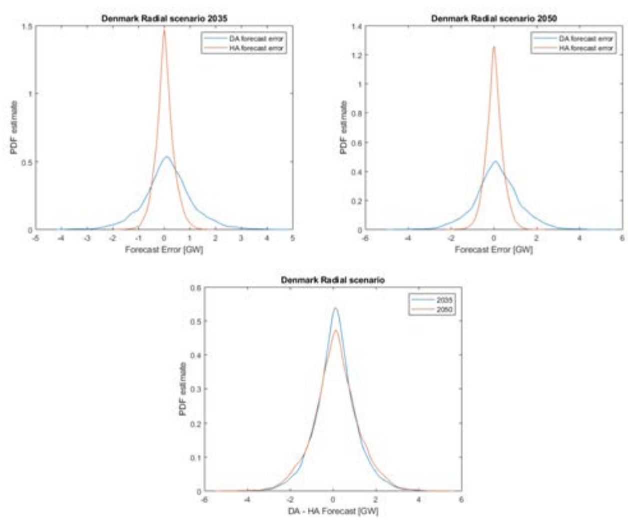

Figure 8 Probability density function for wind power forecast error

The difference between day-ahead wind power forecast error and hour-ahead wind power forecast error is also plotted in Figure 8. This result is coherent with the result of typical week described before that the difference between day-ahead wind power forecast error and hour-ahead wind power forecast error is substantially high. Figure 8 shows that this error is as high as 4 GW. This means that 4 GW of manual reserves might be required to handle the imbalance of day-ahead forecast error. This can be challenging in future scenario since substantial number of conventional generators can be decommissioned. In such scenarios, one of the strategies can be operating wind power plants in deregulated conditions to have reserves required. This is in line to the fact observed in typical week simulation where curtailment of wind power is observed.

IV. Research Questions

The results shown in previous section allows to formulate the following research questions:

- 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?
- 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)?
- How much reserves should be adequate to handle imbalances in the future power system with high share of renewables?
- What kind of technologies would be sufficient for handling the imbalances?
- Can market based solutions be developed for reducing imbalances in the power system with high share of renewable generations?
- What would be the impact of offshore wake in future power system balancing with large share of offshore wind power plants?

To answer these research questions, the value of the developed tool chain is imperative because it is only possible through this tool chain to analyse the impacts of market solutions, technological solutions (like dynamic reserve requirements), forecast simulations, wake modelling, unit commitment, intra-hour balancing optimization etc. at the same time.

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