Modeling the Intra-Hour power system balancing of the Danish Power System for 2020, 2030 & 2050

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***Resumé*—The share of variable renewable energy (VRE) sources, like wind and solar is expected to increase and become major energy resources towards the fossil fuel free energy system. The increase of the variable renewable energy sources in the grid brings new conditions to the energy system due to inherent variability and forecast uncertainty. Power imbalances due to uncertainty of the VRE, such as wind power, poses major challenges for the reliability and security of power system. The authors of this paper analyses the balancing requirements for the Danish power system with large share of renewables for the prognosed energy scenarios of 2020, 2030 and 2050. This is accomplished by modelling Intra-Hour balancing model for Danish network which simulates the creation of power imbalance in the system caused due to Day-Ahead VRE forecast error and imbalance due to hour shift in the generation. The model returns an optimized (in terms of minimizing the social economic cost) plan of the actions required from generators in order to counteract the aforementioned imbalances. The optimization procedure of Intra-Hour market is done in the form of deterministic economic dispatch with one hour optimization horizon. Technical limits such as ramp rates limitations and the maximum generation limit are taken into account by the optimization algorithm.**

I. INTRODUCTION

The increase of the variable renewable energy (VRE) in the grid brings new conditions to the energy system as it comes with the cost of variability in production and uncertainty in the forecasts. Power imbalances created from the variability and uncertainty of the VRE generation, such as wind power, is one of the major challenge for the reliability and security of the power system.

The authors of this paper performed a study on Danish power system considering high wind power penetration. The capability of the power system to be balanced is examined and the most crucial factors affecting the balancing procedure are investigated. That is done by designing an Intra-Hour balancing model which calculates the power imbalance in the system and simulates the necessary balancing procedure. The simulation of the balancing are performed for progonosed scenario of 2020,2030 and 2050. The scope of this paper is to investigate how the increased variability and uncertainty from offshore and onshore wind power plants in the North Sea affects the balancing of the Danish power system and need for reserves. The contribution of this paper are as follows:

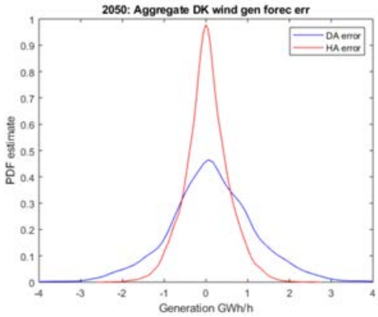
- Quantification of Hour-Ahead imbalance induced in the Danish power system towards 2050 and requirements for the balancing reserves in the Intra-Hour market.
- Analysis of the impact of Intra-Hour balancing optimization for reducing the Real Time imbalance.
- Quantification of the Real-time imbalance in the system towards 2050 and quantification of the automatic reserves needed.

II. SOURCES OF IMBALANCES

Power system imbalance refers to the state in which the power generation not equal to the demand. The first source of imbalances considered are the conventional generators. Steam turbines, gas turbines and combined cycle engines are some of the most utilized conventional generator technologies. As the first scheduling takes place in the Day Ahead market, a plan is created defining generation levels of each producer for intervals of one hour for the next day. Technical specifications are limiting the capability of each generator to follow the aforementioned plan and thus imbalances are created. Finite ramping rates are causes of imbalance in the system as generators are not capable to vary their production level instantly from the one hour interval to the next.

As mentioned earlier, the balancing model uses as input the hourly dispatch plan resulted from the Day Ahead market. In the other hand, the Intra-Hour market aims in the short-term balancing of generation with the demand and thus it is optimized for time steps of 5 minutes. For that reason, during the Day Ahead market the electric load is assumed to variate step-wise due to bidding of block of loads at Day-ahead market. However, with the shorter time intervals resolution of the Intra-Hour market that assumption does not hold anymore. Thus, imbalances are created due to the mismatch of the electric load in the Day Ahead and the Intra-Hour Market.

Another major cause of imbalances in the system is the uncertainty in forecasting of the VRE generations. The uncertainty arising from the winds nature as a physical phenomenon make the wind speed forecasts a key factor in the power balance scheduling. High errors among the wind generation forecasts and the real time generation can force extreme power system balancing problems.



Figur 1. Day-ahead and Hour-ahead wind forecasts error [1]

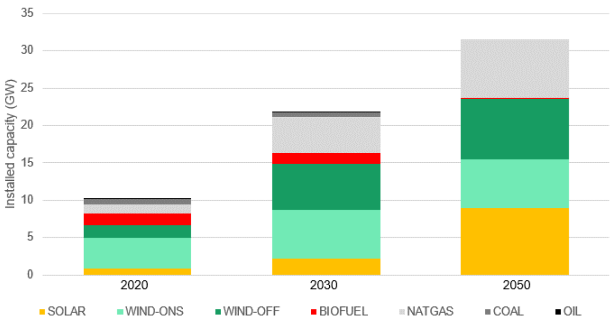
In Fig. 1, the Day-ahead (DA) wind power forecast error and Hour-ahead (HA) wind power forecast error are illustrated for the case of Denmark in the year 2050. As shown, closer to hour of operation, the forecast error reduces and the creation of a new generation schedule, which will minimize the final imbalance, is possible.

It should be noted that load forecast error and imbalance due to disturbance are not considered in this work. Scheduled maintenance of the generators are also not included in this study.

III. Modelling

A. Scenarios

The scenarios used for these studies are based on investment optimization for generation and transmission capacity for North Sea countries performed in Balmorel energy model. The starting point for modelling the generation capacity are the expected installed capacities by 2020. The generation capacity develops for the years 2030 and 2050 through the investment optimization of the model [4]. The development of the installed electricity capacity development towards 2050 is presented in Fig.2. Balmorel contains 3 geographical levels: countries, regions, and areas. Denmark is split into two regions DK1 and DK2.



Figur 2. Aggregated installed electricity capacity development per fuel and scenario.

The tool used to simulate the wind generation time series called CorRES. The capability of CorRes to simulate large-scale variable renewable energy has been proved in [1]. Further information regarding the scenario of simulation and the data used can be found in [5].

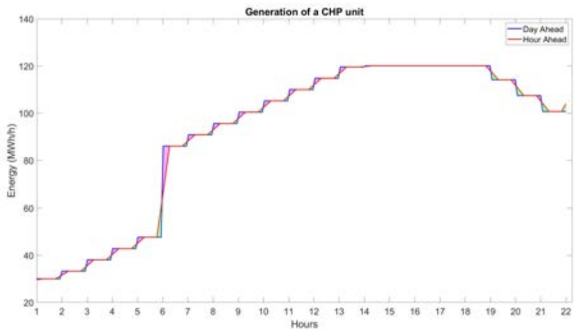
Using these scenarios and CorRES, the optimization regarding the Day Ahead dispatch is run from the Balmorel energy system model in the Balbase4 mode [3].

It should be noted that the heating sector and its interaction with the electricity sector is not considered in the modelling. For that reason, back-pressure CHP power plants are not considered contributing to the balancing process either.

In addition, the balancing operation of neighboring countries to Denmark countries is not simulated. Thus, the model assumes enough support capability in the interconnections. Moreover, it is assumed that Denmark exchange electricity with the other countries during balancing on the day ahead regional prices. In future, the balancing of all the regions will be performed.

B. Modeling the hour shift of conventional generators and interconnection lines

The conventional generators were assumed to start variating their generation 15 minutes before the hour shift and stop 15 minutes after the new hour. During these 30 minutes the conventional generators contribute to the Total Hour Ahead Imbalance (I_{TOTAL}^{HA}). The hour shift of conventional generators is depicted in Fig. 3 by plotting the Day Ahead schedule of a CHP unit together with the respective Hour Ahead before the balancing schedule. The green and the magenta areas between the two curves illustrate the positive and the negative imbalance due to generation shifts (I_S^{HA}) created respectively.

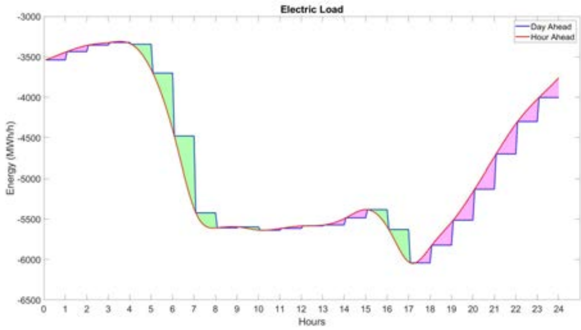


Figur 3. Generation of a CHP unit

The hour shift of interconnection lines was modeled with the same methodology described above.

C. Modeling the electric load in 5 minutes resolution

The electric load time series is assumed to be a smooth function [2]. The time series of the electric load were derived by using splined interpolation in the hourly Day Ahead values. In Fig.4, the electric load in the Day Ahead market is plotted together with the electric load in the Intra-Hour market. The imbalance (I_L^{HA}) created from the electric load is calculated based on the mismatch of these two time series. The green shade area represents the positive imbalance in MWh inducted to the system since the load is lower than what is considered during the Day Ahead market. In the same way, the magenta shade area shows the amount of energy lacking from the system the respective hours.



Figur 4. Electric Load

D. Modelling of the Intra-Hour balancing market

As explained, the Day Ahead optimization of Balmorel model returns a generation plan for all North sea countries. This plan is used as input in the Intra-Hour balancing model together with the hour ahead wind forecasts. Based on the Day Ahead schedule, it is possible to model the hour shift of conventional generators and of the interconnection lines. In that way the imbalance (I_S^{HA}) caused from the hour shifting is calculated. Next, the imbalance (I_{FE}^{HA}) due to the wind forecast error is possible to be determined, since both the Day Ahead generation level of wind generators and the new Hour Ahead forecasts are known. By interpolating the electric load as described previously, the imbalance (I_L^{HA}) induced from the load is also calculated. Aggregating these three imbalances (Eq. 1) leads to the determination of the total Hour Ahead imbalance (I_{TOTAL}^{HA}). In other words, before the balancing optimization takes place the total imbalance of the next hour needs to be calculated and expressed in MWh.

$$I_{TOTAL}^{HA} = I_S^{HA} + I_{FE}^{HA} + I_L^{HA} \tag{1}$$

The balancing model optimizes (in terms of minimizing the social economic cost) the actions required from the generators and the interconnection lines to counteract the aforementioned imbalance. The generators and the interconnection lines change their output in five minute time steps in order the I_{TOTAL}^{HA} to be canceled out and the amount of energy delivered during the whole hour to be exactly as needed. The optimization is done considering the operational costs of each type of generation technology, the cost of fuel, transmission costs and emission taxes.

During both the Day Ahead and the Intra-Hour market, the model is allowed to curtail the wind power generation. The model will choose that option and consequently substitute possible wind energy with a more expensive alternative, obviously, in cases that they system is not able to integrate more wind energy at that given time. During Real Time operation, where the actual delivery of energy occurs, the wind power generation is realized. Thus, in cases where the wind power generators are informed from the TSO during the Intra-Hour market not to offer their maximum but curtail their generation, the Real Time wind curtailment (C^{RE}) can be calculated. As shown in Eq. 2, the C^{RE} is defined as the subtraction of the Hour Ahead wind dispatch (D^{HA}) from the realization of wind (D^{RE}).

$$C^{RE} = D^{RE} - D^{HA} \tag{2}$$

Even between the Hour Ahead schedule and the Real Time generation, there are imbalances I_{TOTAL}^{RE} handled by the automatic reserves close to the delivery time. As the change of the generation levels is modelled in five minute time steps there will still be a remaining imbalance (I_{RM}^{RE}) after the balancing optimization, caused from the conventional generators and the interconnection lines. In addition, in cases where there is no wind power curtailment, if the realization of the wind is higher than the Hour Ahead dispatch, a positive imbalance caused from the forecast error is created in real time (I_{FE}^{RE}). In case of wind power realization lower than the Hour Ahead dispatch negative imbalance I_{FE}^{RE} is induced to the system. The aggregate Real Time imbalance is calculated as in Eq. 3.

$$I_{TOTAL}^{RE} = I_{RM}^{RE} + I_{FE}^{RE} \tag{3}$$

In order the advantages of performing the Intra-Hour market to be depicted in the results of this paper, the total imbalance of the system without performing the balancing optimization is compared with the I_{TOTAL}^{RE}. With no Intra-Hour market, the forecast error and the imbalance which creates (I_{FE}^{NOBAL}) would be calculated as the subtraction of the Day Ahead wind dispatch from the Real Time wind generation taking also into account the curtailment scheduled. The summation of this imbalance with the one induced from the production units during the Day Ahead market (I_S^{NOBAL}) will be equal with the total Real Time imbalance with no Intra-Hour market interfering (Eq. 4).

$$I_{TOTAL}^{NOBAL} = I_S^{NOBAL} + I_{FE}^{NOBAL} \tag{4}$$

The Real Time curtailment of wind without Intra-Hour market (C^{NOBAL}) can also be found as the subtraction of the Day Ahead wind dispatch (D^{DA}) from the realization of wind (D^{RE}).

$$C^{NOBAL} = D^{RE} - D^{DA} \tag{5}$$

The model described is linear and is created in the form of deterministic economic dispatch with one hour optimization horizon.

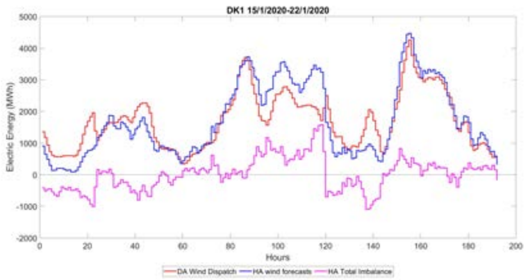
IV. Results

A. Scenario 1: year 2020

In this section, the major results of the simulation are presented. Since the conclusions coming from the study of

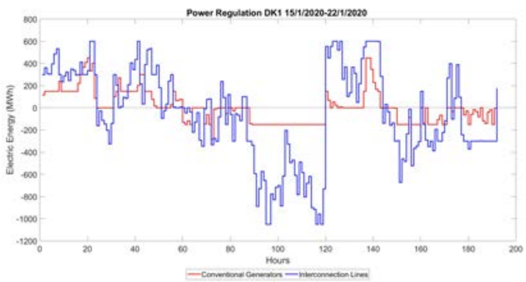
DK1 and DK2 are identical and with purpose of reducing the volume of this paper, only the results of DK1 are presented.

First, in Fig.5 the Day Ahead wind generation dispatch and the Hour Ahead wind forecasts are plotted together for a week of January 2020 in DK1. The I^{HA}_{TOTAL} of DK1 is also depicted in the same figure. The volume of the total Hour Ahead imbalance during this week is 77.2GWh.



Figur 5. The Day Ahead wind generation dispatch, the Hour Ahead wind forecasts and the total Hour Ahead imbalance for a week of 2020 in DK1.

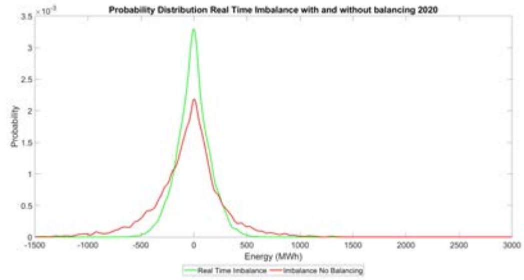
In order the model to counteract the Hour Ahead Imbalance presented above, the generation levels of the connected generators and transmission levels have to be changed. That power regulation during the same week of January 2020 is illustrated in Fig. 6. During the week presented, the maximum up and down regulation is 1.05GWh and -1.2GWh respectively.



Figur 6. The power regulation of conventional generators and interconnection lines for a week of 2020 in DK1.

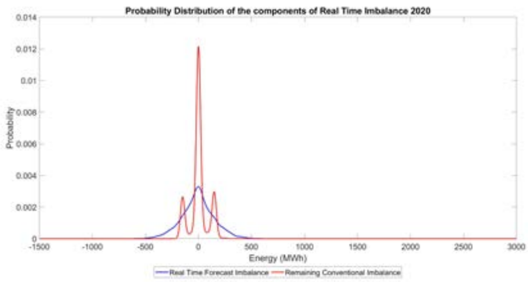
The probability function for the whole year 2020 of the Real Time imbalance is compared with the Real Time Imbalance with no balancing taking place in Fig.7. As shown, the Intra-Hour market reduces the total Real Time imbalance. The volume of the imbalance without the HA balancing is 1.9 TWh while after balancing it is reduced by 45.78% to 1.03TWh. Therefore, it can be seen that when the Intra-Hour market is included the amount of automatic reserves required in the Real Time will also be decreased.

Next, in Fig. 8 the Real Time imbalance is analyzed in its components. As explained, the Real Time imbalance consists of the imbalance due to hour ahead forecasts error and due to the remaining conventional imbalance. The volume of I^{RE}_{RM} and I^{RE}_{FE} is calculated 0.44 TWh and 0.84 TWh respectively.



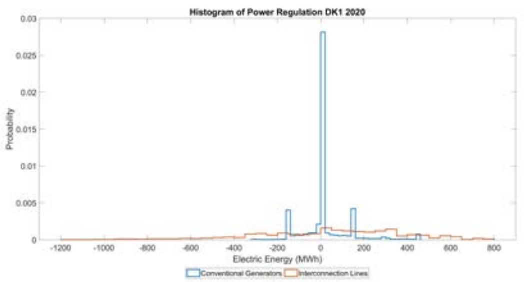
Figur 7. Probability distribution of Real Time imbalance with and without Intra-Hour market for 2020 in DK1.

As expected, the Real Time imbalance is mainly caused from the forecast error.



Figur 8. Real Time: Imbalances due to forecast error and due to conventional generators in 2020 in DK1

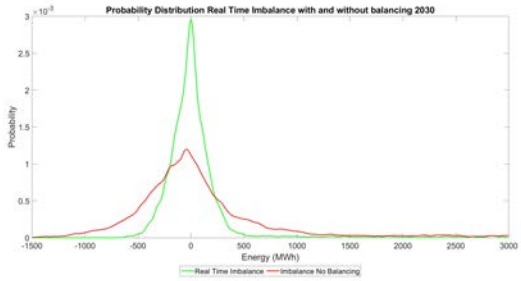
As described, both conventional generators and interconnection lines are regulating their power in order the system to be balanced. In Fig. 9 the histogram of power regulation in DK1 is depicted. It is obvious that interconnection lines are covering a much broader range of imbalances than the conventional generators. The maximum up and down regulation presented during the simulation of 2020 scenario is 1.39GWh and -1.39GWh respectively.



Figur 9. Histogram of power regulation separated by source for DK1 in 2020.

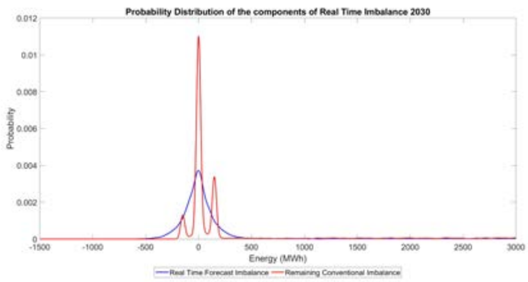
B. Scenario 2: year 2030

In Fig. 10 the probability distribution function of I^{NOBAL}_{TOTAL} and I^{RE}_{TOTAL} when simulating the year 2030 is compared. Again, the Real Time imbalance is lower if the Intra-Hour balancing is performed. The volume of I_{TOTAL}^{NOBAL} and of I_{TOTAL}^{RE} is 3.8 TWh and 1.01 TWh respectively. The total Real Time imblance is reduced when the Intra-Hour market is included.



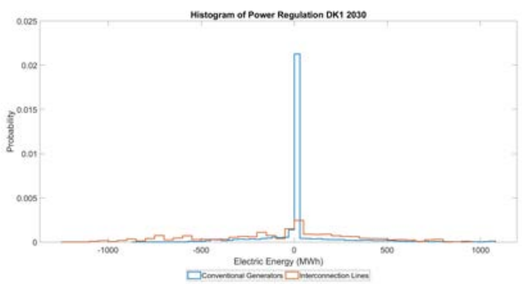
Figur 10. Probability distribution of Real Time imbalance with and without Intra-Hour market for 2030 in DK1.

As expected, the most of the I_{TOTAL}^{RE} is coming from the forecast error in wind generation and that can be seen in Fig. 11. The I_{FE}^{RE} is found to be the major cause of I_{TOTAL}^{RE}. The I_{FE}^{RE} is calculated as 0.77 TWh while the I_{RM}^{RE} is 0.47 TWh.



Figur 11. Real Time: Imbalances due to forecast error and due to conventional generators in 2030 in DK1

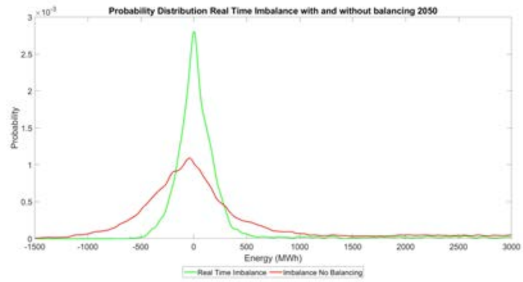
The histogram of power regulation for the scenario of 2030 in Fig. 12 shows that the contribution of the interconnections is incomparable higher than the one of the conventional generators. The maximum up and down regulation is 2.16GWh and -2.92GWh respectively.



Figur 12. Histogram of power regulation separated by source for DK1 in 2030.

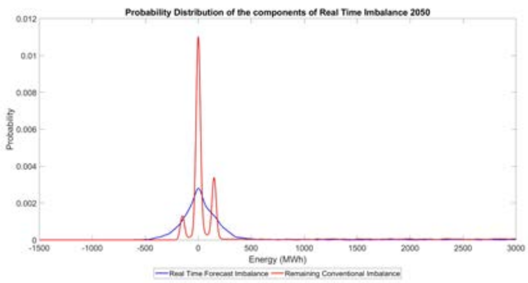
C. Scenario 3: year 2050

Fig. 13 illustrates the probability distribution function of real time imbalances whether the Intra-Hour market is performed or not. The volume of I_{TOTAL}^{NOBAL} and I_{TOTAL}^{RE} is 3.7 TWh and 1.08 TWh respectively.



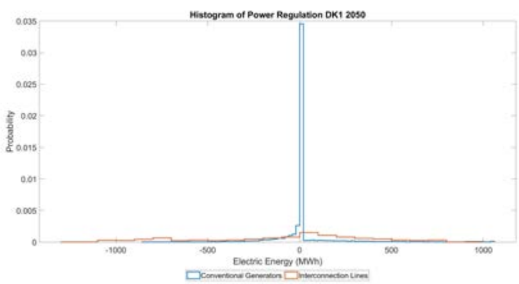
Figur 13. Probability distribution of Real Time imbalance with and without Intra-Hour market for 2050 in DK1.

The Real Time imbalances caused from the forecast error and the conventional generators are presented in Fig.14. The I_{FE}^{RE} is calculated as 0.79 TWh while the I_{RM}^{RE} is 0.49 TWh.



Figur 14. Real Time: Imbalances due to forecast error and due to conventional generators in 2050 in DK1

Finally, the histogram of power regulation for 2050 scenario is illustrated in Fig. 15. The maximum up and down regulation presented during the simulation of 2050 scenario are 2.35GWh and -2.69GWh respectively.



Figur 15. Histogram of power regulation separated by source for DK1 in 2050.

D. Scenario Comparison

The development of the volume of both Hour Ahead and Real Time imbalance is demonstrated in Tab. I. The Hour Ahead imbalance increases towards 2050 due to the expansion of the wind capacity. In the other hand, the Real Time imbalance could be considered as stable among the years. As was expected, the main sources of imbalance for all scenarios is the forecast error .

Tabel I
VOLUME OF IMBALANCES BY SOURCE IN EACH SCENARIO

Imbalances (TWh)	2020	2030	2050
Hour Ahead Renewables	2.64	5.37	6.46
Hour Ahead Conventional	0.49	0.6	0.6
Total Hour Ahead	2.79	5.53	6.6
Real Time Renewable	0.85	0.77	0.79
Real Time Conventional	0.45	0.47	0.49
Total Real Time Imbalance	1.03	1.01	1.08
Total Real Time NOBAL	1.90	3.81	3.70

Furthermore, the minimum and maximum values of the imbalances occurred in each scenario are presented in Tab. II. Based on the maximum and the minimum value of I^{HA}_{TOTAL}, the required amount of balancing reserves for down and up regulation respectively can be measured. In the other hand, the quantification of the I^{RE}_{TOTAL} leads to the measurement of the automatic reserves since the system should be able to be always balanced.

Tabel II
MINIMUM AND MAXIMUM VALUE OF IMBALANCES BY TYPE AND FOR EACH SCENARIO IN DK1.

Imbalances (GWh)	2020		2030		2050	
	Min	Max	Min	Max	Min	Max
HA Renewables	-2.45	1.58	-2.47	4.57	-2.46	4.6
HA Conventional	-0.37	0.2	-0.49	0.334	-0.477	0.352
HA Total	-2.464	1.644	-2.490	4.664	-2.485	4.740
RT Renewable	-0.635	0.604	-0.731	0.604	-0.731	0.568
RT Conventional	-1.232	0.150	-0.528	0.159	-0.520	0.150
RT Total	-1.155	0.604	-0.881	0.649	-0.731	0.718
RT NOBAL	-2.365	1.392	-4.094	3.385	-4.094	3.384

Lastly, the mean and the volume of wind curtailment for each scenario are shown in the Tab.III. The amount of curtailed energy produced from wind is growing towards 2050 as the imbalances are also increasing. In the same table, a comparison between the C^{RE} and C^{NOBAL} is made. It is clearly demonstrated that by including Intra-Hour market in the generation scheduling procedure the wind curtailment is considerably reduced.

Tabel III
MEAN AND VOLUME OF WIND CURTAILMENT WITH AND WITHOUT INTRA-HOUR MARKET FOR EACH SCENARIO.

Years	RT Curtailment		NOBAL Curtailment	
	Mean (MWh)	Volume (TWh)	Mean (MWh)	Volume (TWh)
2020	3.02	0.03	12.37	0.11
2030	224.09	1.96	532.99	4.66
2050	331.77	2.90	741.93	6.48

V. CONCLUSIONS

The authors of this paper performed a study of the balancing of danish energy system in the years 2020, 2030 and 2050 considering high wind power penetration. The research questions set in the beginning of this paper are finally answered as follows.

- Regarding the first research question set, the Hour Ahead imbalance increased towards 2050 as the share of variable energy increased in the system. The volume of the total Hour-Ahead imbalance for each scenario was calculated in Tab. I. The maximum and minimum values of the total Hour Ahead imbalance presented in Tab. II can be also considered as the minimum down and up balancing reserves required.
- Regarding the second research question set, the results of this paper showed that Hour Ahead planning and taking advantage of the more accurate forecasts improves the Day Ahead schedule in terms of Real Time imbalances and Real Time wind curtailment. The probability function of the total real imbalance proved that by adjusting the Day Ahead schedule accordingly the resulting imbalance is more controllable. The volume of the Real Time imbalance as well as the total amount of wind curtailment are reduced when Intra-Hour market takes place for all simulated scenarios.
- Regarding the third research question set, the volume of Real Time imbalance was quantified in Tab. I for each scenario. The minimum automatic reserves required are determined through Tab. II and the extreme values of total Real Time imbalance.

To conclude, large Hour Ahead imbalances will have to be counteracted in the near future making the study of balancing the system necessary. Thus the capacity of balancing reserves should grow in order the system to be able to withstand the increasing Hour Ahead imbalances. By utilizing tools like the one proposed in this paper, the Real Time imbalances passing to the automatic reserves can be minimized. Furthermore, the simulations demonstrated the dominant role of interconnection lines in Intra-Hour market as Denmark was mainly balanced from its neighbours in all scenarios of simulation.

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