

System Balancing with 6 GW Offshore Wind Energy in the Netherlands

Instruments for Balance Control

M. Gibescu

A.J. Brand

W.W. de Boer

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System Balancing with 6 GW Offshore Wind Energy in the Netherlands – Instruments for Balance Control

M. Gibescu, A.J. Brand and W.W. de Boer

Abstract – This paper investigates various alternatives for balance control as may be required by the addition of 6 GW offshore wind in the Netherlands. First, a survey of international experiences with regards to balancing the extra variability and limited predictability introduced by wind energy into power systems is presented. Next, the influence of forecast lead time and aggregation level on the accuracy of short-term wind power predictions is investigated. The importance of continuous wind power forecast updates, which allow for a better allocation of the forecast errors within the operation of conventional generation units in the system, is shown. Pumped storage, compressed air energy storage (CAES), and a combination of pumped storage and fast start-up units are compared in terms of their ability to smooth out imbalances due to wind power forecasting errors. In addition, an inverse offshore pump accumulation system (IOPAC) and its control strategy are presented. This storage solution is found to be more efficient at reducing the system imbalance, due to its ability to intelligently trade in the day-ahead market. It is shown that aggregating forecast errors at the system level requires less overall reserves; by contrast the advantages of central versus distributed control for the storage system are not obvious. Finally, the concept of shutting down a wind farm gradually as a linear function of increasing wind speed is demonstrated to be better than abrupt shut-down. We conclude with a summary of candidate instruments for balance control that would be most applicable to the foreseen wind energy growth in the Netherlands.

Index Terms—Wind energy, Power system balancing, Wind power forecasting, Energy storage, Wind farm control

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M. Gibescu is with the Delft University of Technology, Delft, Electrical Power Engineering, Netherlands; m.gibescu@ewi.tudelft.nl.

A.J. Brand is with Energy Research Centre of the Netherlands ECN, Unit Wind Energy, Petten, Netherlands; brand@ecn.nl.

W.W. de Boer is with KEMA Consulting, Arnhem, Netherlands; wouter.deboer@kema.com.

1. INTRODUCTION

IN preceding studies growth scenarios for on- and offshore wind energy in the Netherlands up to the year 2020 were developed and estimates for balancing requirements were given [1]-[2].

In a subsequent study [3] it was shown that the estimated wind power variability associated with 8000 MW (6000 MW offshore + 2000 MW onshore) installed capacity can easily be handled by the ramp rate abilities of conventional units expected to be available in 2020. In this paper we focus on the remaining integration issue for wind power in the Netherlands, namely its limited predictability. To this end we first present international experiences with instruments for balancing wind power and with design of balancing markets (section II). Next, we analyze a number of these instruments in the context of the Dutch power system (section III). We conclude with a summary of candidate instruments for balancing wind power forecasting errors that would be most applicable to the future wind energy growth scenario for the Netherlands.

2. International Experience

2.1 Overview

We begin with a short survey of international experiences with instruments for balancing the variability and forecasting errors introduced by large-scale wind integration into a power system. The focus is on wind power forecast updates (section II.B), aggregation of wind power (section II.C), energy storage (section II.D), and wind farm control (section II.E). In addition, the design of balancing markets is addressed in section II.F.

2.2 Wind Power Forecast Updates

The quality of wind power forecasts significantly improves as the forecast horizon decreases [4]. The state-of-the-art indicates that the capacity normalized root mean square error (cRMSE) may reach a minimum value of 2...3% for a lead time of 2 hours before delivery [5]. For example in Germany this significant improvement in the accuracy of wind power forecasts consequently allowed for a better commitment and dispatch of the other generation units [5]. By doing so, the reserves held for wind

power were decreased and the resulting surplus power could be offered by the conventional units in e.g., the intra-day market. Also a more efficient use was made of the available ramping capabilities of different units.

2.3 Aggregation of Wind Power

Aggregation of wind power over a larger geographical area, apart from smoothing out variability, improves the quality of the forecast because of the partly uncorrelated character of the forecast errors [4], [6]. As a result, both the reserves held and the reserves actually applied in a control area are decreased. Balancing wind power across control areas is even more efficient [5].

2.4 Energy Storage

Due to the relatively high investment costs of large-scale energy storage technologies, storage has to be multi-functional and market-driven, rather than employed only in order to reduce imbalances resulting from wind energy.

In the Netherlands, several ongoing studies are devoted to cost-benefit analysis for large scale energy storage systems [7]–[8]. In [8], an energy storage system has been proposed that would provide the following functions:

- Download capacity for wind power at night during high wind and light load periods;
- Download capacity at night for base-load units that cannot be switched off, coupled with additional production capacity during peak load;
- Extra production capacity during periods with cooling water discharge restrictions for conventional plants, and
- Primary action.

Section III.D describes the benefits of such a system when it is used to perform the first function.

2.5 Wind Farm Control

Although in a technical sense clustering of wind farms into a virtual power plant may provide benefits for active power management and reactive power control, it is not economically attractive to operate such a plant for power balancing if the market design penalizes curtailment, as shown in Germany [9]. However, occasional use of wind farms to provide downward regulating power may be attractive during certain periods, e.g. when the surplus price is negative.

2.6 Balancing Market Designs

As to the market design for balancing services, there are major differences between various countries [10], where each market design has an unique impact on how balancing is actually provided. For example, there are differences in the institutional environment where the responsibility for taking care of imbalances arising from wind power either is assigned to a system operator (Germany, Spain, and Denmark for onshore wind power) or to a market party (the Netherlands, U.K. and Denmark for offshore wind power). Also, differences exist in the rules of use and provision of balancing services. In the following we list a number of developments.

In the past years progress has been made to increase

the liquidity of intra-day markets. Gate closure times of about one hour ahead of delivery (such as in the Netherlands) are sufficient to increase the accuracy of wind energy predictions to an acceptable level. This is in addition to the single-buyer balancing market, which is operated by the TSO.

Power systems with dual imbalance pricing are problematic for wind energy due to the high penalties imposed, e.g. in the United Kingdom. To minimize imbalance costs, market parties should aggregate their production portfolios [11].

If market parties employ wind power forecasts without being made responsible for balancing, their aim would be to optimize financial gains rather than to minimize their imbalance. This is why in such cases aggregated wind power forecasts have to be managed by the transmission system operator (TSO).

There is a clear trend in Europe towards more cross-border balancing, which certainly promises advantages for wind power [10]. Balancing geographically larger control areas will provide benefits for wind power, not only because of overall decreased variability and increased predictability, but also because of larger market volumes and larger balancing resources.

Finally it is noted that in all European countries the present organization of support schemes – which to date remains the major source of revenues for wind power producers – discourages the use of curtailment as a balancing instrument. Controlling the power output of wind farms must therefore be considered as an option from a power system operations perspective, since the opportunity loss by curtailment is significant.

3. Instruments for Balancing Wind Energy

3.1 Outline

The following instruments for balancing wind power forecasting errors in the Netherlands are analyzed: short-term forecast updates and aggregation (section III.B), pumped storage, compressed air storage and fast start-up units (section III.C), and inverse pumped accumulation (section III.D). In addition, a wind farm shut-down strategy is presented in section III.E.

The analysis is valid for the scenario with 7.8 GW of installed wind power in the year 2020 [1]. The time series of produced and forecasted 15-minute average wind power are the same as employed in our preceding study [2], and include four different day-ahead forecasts issued at 24, 18, 12 and 6 hours before delivery.

3.2 Short-term Forecast Updates and Aggregation

3.2.1 Influence of Forecast Lag on System Imbalance

The accuracy of wind power forecasts is evaluated by comparing the forecasted values to the produced amounts. The key indicator is the capacity normalised mean of the absolute forecast error (cNMAE) [12]. As table I shows, the impact of bad day-ahead forecasts can be alleviated by making use of forecast updates. This

clearly shows the importance of continuous wind power forecast updates, which will also allow for a better allocation of the forecast errors within the operation of other generation units in the system.

TABLE I
CAPACITY NORMALIZED MEAN ABSOLUTE FORECAST ERROR (cNMAE)
FOR DIFFERENT DAY-AHEAD FORECASTS [13]

Forecast lag before delivery	cNMAE [%]	
	Min	Max
24 hours	10.5	13.5
18 hours	10.0	13.0
12 hours	9.0	11.5
6 hours	8.5	11.5

Another indicator for the forecast accuracy is the capacity normalized standard deviation of the wind power forecast error (cNRMSE). As shown in fig. 1, the cNRMSE is found to drop to half between the forecasts performed at 36 hours and 3 hours before delivery.

It should however be noted that neither the NMAE nor the NRMSE of forecasts based on numerical weather prediction models reduce to zero if the forecast lag approaches present time because of the intrinsic uncertainty in these models. Such a reduction however can be achieved if online production data is included in the forecasts, as is done in fig. 1, also showing the cNRMSE for the 0 to 6 hours before delivery.

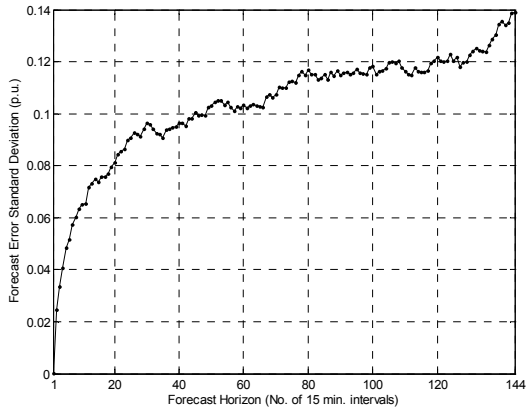


Fig. 1 – Capacity normalized standard deviation (cNRMSE) of the wind power forecast error, 7800 MW scenario.

3.2.2 Aggregation of Forecast Errors at PRP Level versus Central Level

The impact of aggregation of wind power on imbalance due to wind power forecast errors is investigated on the basis of forecasts issued 24 hours before the day of delivery. Two aggregation levels are considered: the system level and the programme responsible party (PRP) level. This consists of seven individual market parties, each with some wind power as part of their portfolio. The hypothesis is that a central aggregation would allow internal cancelling out of forecast errors. It is found that this indeed is the case: aggregation at the system level requires about 6% less overall reserves for the compensation of forecast errors (this is the percent reduction in the length of the confidence interval, as computed from table II).

TABLE II
RANGE AND CONFIDENCE INTERVAL OF WIND POWER FORECAST ERROR
FOR SUM OF INDIVIDUAL PRPS AND SYSTEM

	Wind power forecast error		
	Max. [MW]	Min. [MW]	99.7% C.I. [MW]
Sum PRPs	+5257	-5450	[-3754 ... 4071]
System	+5148	-5326	[-3482 ... 3907]
Difference	109	-124	[-272 ... 164]

3.3 Pumped Storage, Compressed Air Energy Storage and Fast Start-up Units

3.3.1 Methodology

In this section, pumped storage and compressed air technologies of similar energy content are compared. It is assumed that the storage system does not participate in any market trading, in order to focus on the effectiveness of various technologies in reducing imbalances arising from wind speed forecasting errors. As a further simplifying assumption, we allow the storage system to reverse operation between consecutive Programme Time Units (PTU, 15-minute intervals), i.e. from charging to discharging and vice versa, depending on the sign of the forecast error.

The following comparably-sized storage systems are analyzed for the scenario with 7800 MW installed wind power, and a 24-36 hour lead time for the wind forecasts:

- A pumped storage (PS) system of 10.08 GWh, charging time 8 hours, hence 1260 MW installed power, with a 0.81 round-trip efficiency, i.e. equal 0.9 pumping and generating efficiencies, with efficiencies independent of charging levels.
- A compressed air energy storage (CAES) system of 7.2 GWh, charging time 8 hours, with a 0.8 compression efficiency and a 1.4 charge efficiency factor, which means that the amount of energy that can be generated at full discharge is $7200 \times 1.4 = 10.08$ GWh, thus equal to the pumped storage.

In addition, the effect of 852 MW of installed fast start-up units on the reduction of negative imbalances (less wind power than predicted) is analyzed. Negative imbalances are considered more dangerous to system reliability than positive ones, which can ultimately be taken care of by curtailing excess wind production. The fast start-up units are supposed to complement the pumped storage and so the value of 852 MW was chosen as equal to the standard deviation of the imbalance remaining in the system after the implementation of the 10.08 GWh pumped storage system. It is assumed that the fast start-up power can be switched on or off in increments of 2 MW, and reacts to correct imbalances whose absolute value is bigger than 200 MW. This prevents an unnecessarily large number of start-ups and shut-downs in cases when the imbalance is less than 200 MW and can thus be covered from the spinning reserve carried by conventional units on-line. It is assumed that the fast start-up units are open-cycle gas turbines (OCGT), and hence are capable of starting and ramping up to their installed capacity within one PTU, i.e. 15-minute time interval.

3.3.2 Results for Central Level Aggregation

As an illustration, fig. 2 shows a 52-day (5000 PTUs) sample from the yearly time series for the original and the reduced imbalance after the application of a 10.08 GWh pumped storage system in combination with 852 MW installed capacity from fast start-up units.

Results from the comparison of the various technologies are summarized in table III, which shows the reduced standard deviation and the average positive and negative imbalances, all in terms of per unit with respect to their original values.

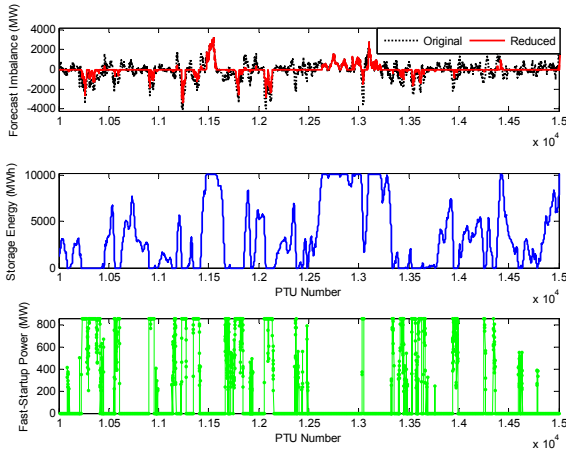


Fig. 2 – Time series for 52 days of forecast imbalance, state-of-charge and fast start-up power with a 10.08 GWh pumped storage system and 852 MW open-cycle gas turbines.

In addition, the reduced 99.7% confidence intervals for the aggregated forecast error are shown in the last row. As a reference point, the original confidence interval before applying any storage was [-3948 ... 3441] MW.

TABLE III
STATISTICAL PROPERTIES FOR THE SYSTEM IMBALANCE REDUCTION

	10080 MWh Pumped Stor- age	7200 MWh CAES	10080 MWh PS 852 MW Fast Start-Up
σ [p.u.]	0.84	0.84	0.66
μ^+ [p.u.]	0.61	0.68	0.61
μ^- [p.u.]	0.68	0.64	0.25
99.7% C.I. [MW]	[-3530..3310]	[-3421..3326]	[-2678..3310]

From table III it can be seen that it is easier for the pumped storage system to take care of positive (excess wind) imbalances. This is because the 0.9 pumping and generating efficiencies lead to consuming 111% more energy than stored from the positive (excess wind) forecasting errors, whereas only 90% of the stored energy can effectively be used when discharging to cover for negative (deficit wind) errors. The overall standard deviation has been reduced by the CAES system to the same value as in the case of the PS system, i.e. 84% (from 1013 to 852 MW). By contrast, the CAES system, thanks to its charge efficiency factor of 1.4, is slightly better at taking care of negative imbalances than a PS system of comparable installed capacity. However, unlike PS, a CAES "discharge" implies burning of fuel (gas) and hence extra emissions and higher operating costs.

The technology for diabatic CAES systems is avail-

able and already has been applied successfully, e.g. the Huntorf plant in Germany, already in operation for about 20 years. In the Netherlands there are a small number of caverns (unused salt domes) which can be used for CAES. However these caverns are more favorable for storing gas or CO₂. For this reason it is concluded that CAES development in the Netherlands will be hard and will have to compete with other technologies.

The last column of table III shows the results for the pumped storage and fast start-up units combination. The resulting reduction in average negative imbalance is to 25% of its original value, which is achieved with an average of 6.5 start-ups per day. The reduction in positive imbalance is naturally the same as that without the fast start-up units, whereas the overall standard deviation is now reduced to 66% (667 MW).

3.3.3 Results for PRP Level Aggregation

The installed 7800 MW wind power is now distributed over seven market parties at the programme responsible party (PRP) level. In order to facilitate comparison with the results for the central level aggregation, the installed storage and fast start-up capacities are allocated proportionally to the installed wind power of each PRP. These installations are now controlled to correct the individual imbalances due to forecasting errors as experienced by each PRP. Fig. 3 shows the reductions in negative imbalance for central versus PRP level aggregation, for various technologies, and increasing values of storage capacities, up to 30 GWh. From this figure we note that installing storage and/or fast start-up units to be controlled for reducing the imbalance at central level is slightly more advantageous than at the PRP level in terms of reducing the average negative imbalance. The advantage stays approximately constant regardless of storage capacity, with the largest difference experienced for the PS and fast start-up combination, at about 0.12 p.u., which translates to 86 MW. By contrast, installing storage and fast start-up units to be controlled for reducing the imbalance at PRP level is slightly more advantageous than at the central level in terms of reducing the total spread -- or standard deviation -- of the imbalance. The advantage increases with higher storage capacities, with the largest difference being about 0.025 p.u., which translates to about 25 MW.

It is concluded that differences between central and market participant level aggregation seem insignificant from the standpoint of being more or less effective in reducing the forecast imbalance. It follows that decisions about where storage units are to be installed and how they are to be controlled will probably be governed more by geographical constraints, considerations about economies of scale, ease of accounting, technical accessibility and confidentiality of control signals.

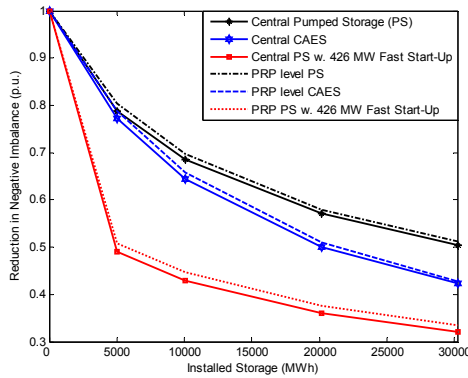


Fig. 3 – Reductions in average negative imbalance for PS, CAES and PS with 426 MW fast start-up units for PRP versus central level aggregation.

3.4 Inverse Offshore Pump Accumulation System

Next we consider an inverse offshore pump accumulation system (IOPAC) [8]. The IOPAC has been proposed to be stationed on an “Energy Island”, that is an artificial island at sea consisting of a ring of dikes (5x8 km²) enclosing a deep dredged reservoir. The intended depth of the reservoir is 50 m below sea level, and the water level of the reservoir will typically vary between -32 and -40 m. Fig. 4 gives an impression of this concept.

The IOPAC is equipped with a control system that aims to prevent the storage from being saturated at any point in time, and thus makes it more capable of reducing the imbalance due to wind energy. The strategy of the control system involves selling power during peak hours (8 am to 11 pm) if the water level is too low, and buying power during off-peak hours if the water level is too high. In this way the control system keeps the water level around the half-full operating point (around -36 m).

Energy is bought from or sold to the day-ahead market, assuming any needed energy volume is available within the limits of the storage device. On a day-ahead basis this is feasible; whether there is a surplus or a shortage of energy in the reservoir can be noticed by simply monitoring the water level. The lower part of fig. 5 shows this correction signal (where positive power means bought from the market and used to charge the storage system).

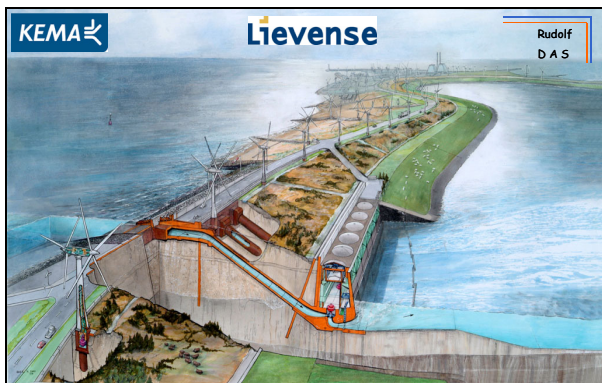


Fig. 4 – Concept of the Energy Island with an inverse pump accumulation system (IOPAC).

The effectiveness of the IOPAC in alleviating imbalance is analyzed by considering a pump/turbine power

rating of 2000 MW, with a storage energy capacity of 30 GWh. Initial imbalances result from wind power forecasts issued at noon before the day of delivery (with a lag of 12-36 hours). The upper part of fig. 5, showing the impact of the control system on the variation of the water level as a response to these imbalances, reveals that the control system prevents the water level from drifting away. Fig. 6 shows the original imbalance, the imbalance after employing the IOPAC alone, and the imbalance for the IOPAC with intelligent control strategy. The imbalance reduction, measured in terms of per unit standard deviation with respect to the base-case, ranges from 0.714 (IOPAC alone) to 0.697 (IOPAC with intelligent control). Some imbalance remains after the application of IOPAC, but this could be handled by fast responding conventional units and/or combining these measures with short-term wind power forecasts.

The proposed intelligent IOPAC is therefore shown to alleviate imbalances due to wind power forecast errors.

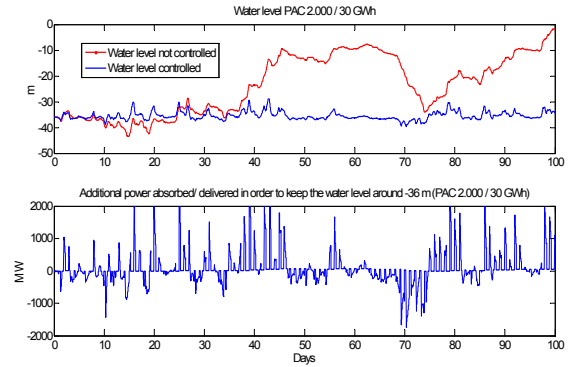


Fig. 5 – Impression of average power absorbed/delivered in order to maneuver the IOPAC around the half-full operating point.

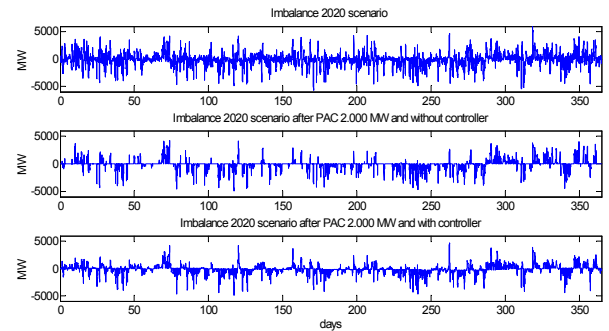


Fig. 6 – Imbalance before and after the application of IOPAC storage, 2000 MW installed power, with 30 GWh energy capacity.

3.5 Wind Farm Shut-down Strategies

Finally, the impact of wind farm shut-down strategy on the imbalance is analysed. We consider two shut-down strategies. In the abrupt shut-down strategy, a wind farm is shut down within 10 seconds if the 15-minute averaged wind speed exceeds 25 m/s, and is started up again within 10 seconds if the 15-minute average wind speed is less than 22 m/s. In the gradual shutting-down strategy, on the other hand, the power of a wind farm varies linearly with the wind speed between full load and zero if the 15-minute averaged wind speed is between V_3 and V_4 as indicated in fig. 7 (22 and 25 m/s respectively).

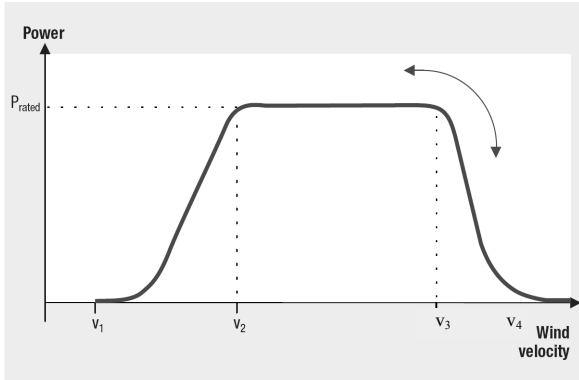


Fig. 7 – Concept of gradual ramping up/down between V_3 and V_4 at high wind speeds; Source: Enercon.

In practice the abrupt shut-down strategy or a close variant is applied, where the turbines in a wind farm may either shut down individually based on their individual wind speed measurements or collectively based on one central wind speed measurement system in the wind farm. In this analysis a whole wind farm shuts down based on its 15-minute averaged wind speed. Also, in reality the shutting-down and starting-up times may differ from the value of 10 s employed in this analysis. These choices however do not strongly affect the conclusions.

We analyze the 15-minute average wind speeds at the wind farm locations foreseen in the Netherlands for the period of one year. It is found that on three days the wind speed exceeds 25 m/s in at least one location. We selected day 222 for further analysis, and present the wind speeds in fig. 8. It should be noted that the wind speed does not exceed 25 m/s at all wind farms, so that not all wind farms shut down.

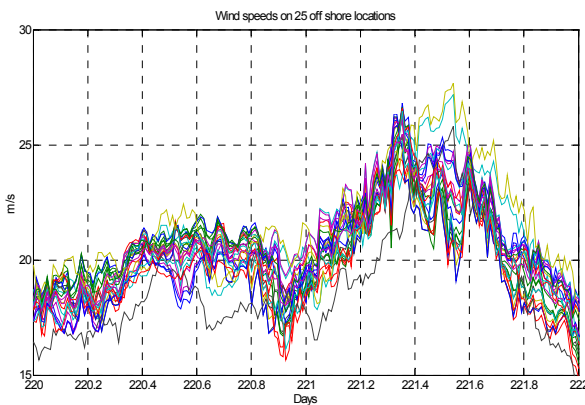


Fig. 8 – The wind speed at the 25 offshore locations during one day with wind speeds exceeding 25 m/s.

As shown in figures 9 and 10, with the abrupt shut-down strategy, there are large differences between the forecasted and the produced wind power, and, as a consequence, larger imbalances. With the gradual shut-down strategy, the differences are significantly less. It was found that with gradual shut-down the imbalance due to forecasting errors is reduced by more than 50% as compared to abrupt shut-down. In addition, benefits in terms of decreasing the variability in the wind power output can also be observed in fig. 9.

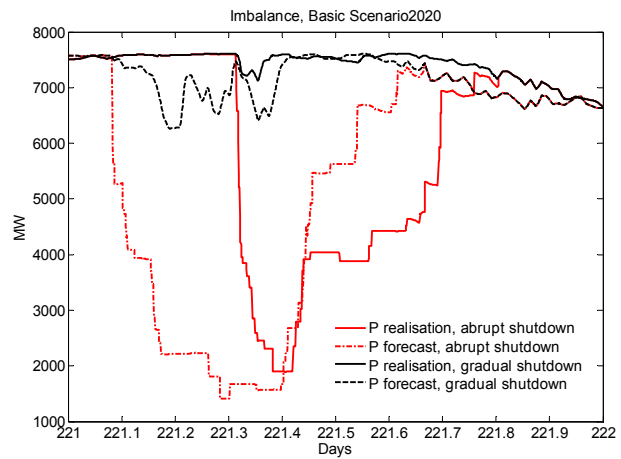


Fig. 9 – Wind power production and forecast during the day with wind speeds over 25 m/s and after applying the abrupt and gradual shut-down strategies.

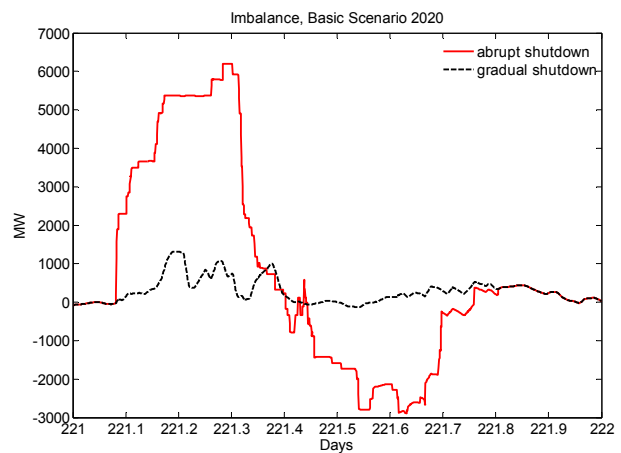


Fig. 10 – Remaining forecast imbalance during the day with wind speeds over 25 m/s and after applying the abrupt and gradual shut-down strategies.

The concept of shutting down the wind farm gradually as a linear function of the (high) wind speed is therefore found to be significantly better than abrupt shut-down.

4. Summary and Conclusion

In this paper we investigated various alternatives for balance control as required by the addition of 6 GW offshore wind in the Netherlands. First we presented a survey of international experiences with regards to balancing the extra variability and limited predictability introduced by wind energy into power systems. Next, the influence of forecast lead time and aggregation level on the accuracy of short-term wind power predictions was investigated. The importance of continuous wind power forecast updates, which allow for a better allocation of the forecast errors within the operation of conventional generation units in the system, was shown. Also the benefit of balancing forecasting errors at the central level over the Programme Responsible Party (PRP) level was shown. Pumped storage, CAES, and a combination of pumped storage and fast start-up units were compared in terms of their ability to smooth out imbalances due to wind power forecasting errors. The advantages of central versus distributed control for the storage system were not found to be significant. In addition, an inverse offshore

pump accumulation system (IOPAC) and its control strategy were presented. This storage solution is found to be more efficient at reducing the system imbalance, due to its ability to intelligently trade in the day-ahead market by taking advantage of price differentials between day and night. Finally, the concept of shutting down a wind farm gradually as a linear function of increasing wind speed was demonstrated to be significantly better than abrupt shut-down. From this analysis it can be concluded that the following instruments for balance control are most applicable to the foreseen wind energy growth in the Netherlands: continuously updated short-term forecasts, pumped-accumulation storage systems, fast start-up units, and gradual shut-down strategies for wind farms.

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BIOGRAPHIES

Madeleine Gibescu received her Dipl.Eng. in Power Engineering from the University Politehnica, Bucharest in 1993 and her MSEE and Ph.D. degrees from the University of Washington, Seattle, U.S., in 1995 and 2003, respectively. She has worked as a Research Engineer for ClearSight Systems of Kirkland, Washington, and as a Power Systems Engineer for the AREVA T&D Corp. of Bellevue, Washington, U.S. She is currently an Assistant Professor with the Electrical Power Systems group at the Delft University of Technology, Netherlands. She is a member of the IEEE. Her research interests include power system economics, power system security under open access, and operations planning for systems with significant wind power.

Arno J. Brand is a research scientist in the unit Wind Energy of the Energy Research Center of the Netherlands ECN. He has a M.S. degree (1987) in applied physics and a Ph.D. degree (1992) in Mechanical Engineering, both from the Delft University of Technology, Netherlands. His dissertation work was on the structure of the turbulent boundary layer. Dr. Brand has been employed in wind energy at ECN since 1991. Up to 1999, he was mainly involved in experimental and computational wind turbine rotor aerodynamics. In this context he participated in four projects under the European Non-Nuclear Energy Programme and two Tasks of the International Energy Agency. In 1998 he got involved in wind energy meteorology, with the emphasis on short-term prediction and wind resource assessment. Recent and current projects are on the wind (power) resource of the North Sea (www.ecn.nl/wind/other/offshorewindatlas), renewable energy forecasting (www.ecn.nl/avde), the integration of wind power into the grid, and the (mutual) effect of wind farms on the wind resource. Dr. Brand was secretary of Netherlands Wind Energy Association NEWIN (2000-2006) and has been a member of the Steering Committee Wind Technology of KiviNiria (since 2003). His research interests include fluid dynamics (experimental as well as numerical), aerodynamics, turbulence, and statistics.

Wouter W. de Boer obtained a M.S. in Mechanical Engineering in 1987 (speciality Control Engineering) from Delft University of Technology, Netherlands. Thereafter he joined KEMA Consulting in Arnhem, Netherlands. Within KEMA he developed himself further as an expert in the modelling and control design of energy-relates conversion systems. Specifically, modelling and control design has been carried out for wind turbines, fossil fired power plant, automatic generation control (AGC), boiling water reactors, fuel cells and greenhouses. The modelling and control design tools include: PC Matlab/Simulink, ACSL, MMS, TRAC_P(B) and PCTRAX. He also conducted condition-monitoring projects for gas turbines (thermodynamic and mechanical) and for wind turbines (mechanical). He has worked on several developments concerning the liberalization process, such as choice of program time unit, secondary power control, optimal scheduling units and assessment of the impact of large scale wind energy. Mr. de Boer also prepared a course for Mechanical Engineers in Power Plants (course REWIC C, subject: "Model based control design methods").



System Balancing with 6 GW Offshore Wind Energy in the Netherlands – Instruments for Balance Control

Madeleine Gibescu, Delft University of Technology

Arno Brand, Energy Research Center Netherlands

Wouter de Boer, KEMA Consulting (presenter)

7th International Workshop on Large Scale Integration of Wind

Power into Power Systems

Madrid, May 26-27, 2008

Experience you can trust.

Contents

- Overview of the project
- Analysed measures to reduce imbalance
 1. Short term forecast
 2. Aggregation of forecast error
 3. Pumped storage in combination with fast power units
 4. Inverse Off shore Pump Accumulation system
 5. Shutting down strategies
- Conclusions and recommendations



Overview project

- Analysis impact of 2020 wind energy scenario:
6.000 MW off shore + 1.800 MW on shore w.e.
on Dutch market design
- Dutch Market design:
 - E-program (15 minute resolution, 24 hrs ahead)
 - Program responsible (PR) to realise the E-program, otherwise imbalance costs
 - TSO TenneT balances the imbalance with help of secondary control (AGC)

Goals of the project

1. What are the wind power variations within 15 minutes? (responsibility of TSO (TenneT)
2. What are the windpower variations >15 minutes? (PR)
3. Is the current Dutch market design adequate enough wind power?
4. Analysis of measures to reduce imbalance

Approach

- Power variations within 15 minutes due to nature of wind variations → modelling approach
- Power variations >15 minutes
Approach:
 - Real wind speed data
 - Deriving corresponding wind forecast data (12-36 hours ahead)
 - Interpolating them to intended wind farm location
 - Modelling / simulating impact wind power



Main findings first part of study

Impact wind power: 6 GW off shore + 1,8 on shore

- Power variations within 15 minutes are in the same range as current ACE ($\sigma \sim 40$ MW)
→ 2 x ACE with wind power
- Power variations >15 minutes due to forecast errors (analysed: 12-36 hours ahead)
 - Structural due to forecast errors at partial load
[-3530 .. 3310] MW 99.7% Confidence interval
 - Incidental due to forecast errors during storm fronts (5.000 MW)



Analysed measures to reduce imbalance

1. Short term forecast
2. Aggregation of forecast error
3. Pumped storage in combination with fast power units
4. Inverse Off shore Pump Accumulation system
5. Shutting down strategies



Analysed measures to reduce imbalance: 1. Short term forecast

- Hirlam model (ECN)
- cNMAE = capacity normalised mean of the absolute forecast error

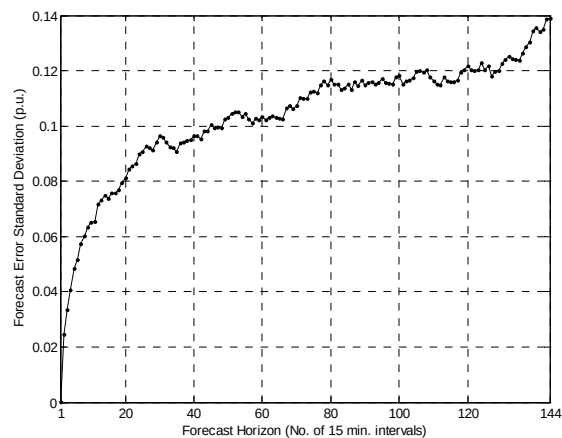
Forecast lag before delivery	cNMAE [%]	
	Min	Max
24 hours	10.5	13.5
18 hours	10.0	13.0
12 hours	9.0	11.5
6 hours	8.5	11.5



Analysed measures to reduce imbalance:

1. Short term forecast

- cNRMSE = capacity normalized standard deviation of the wind power forecast error.



Analysed measures to reduce imbalance:

2. Aggregation of Forecast Errors

Two aggregation levels are considered:

1. System level
2. Programme responsible party (PRP) level,
7 individual PRP's in NL

Hypothesis is that a central aggregation would allow internal cancelling out of forecast errors.

Analysed measures to reduce imbalance: 2. Aggregation of Forecast Errors

Results:

aggregation at the system level requires about 6% less overall reserves for the compensation

	Wind power forecast error		
	Max. [MW]	Min. [MW]	99.7% C.I. [MW]
Sum PRPs	+5257	-5450	[-3754 ... 4071]
System	+5148	-5326	[-3482 ... 3907]
Difference	109	-124	[-272 ... 164]

6% reduction in the length of the confidence interval

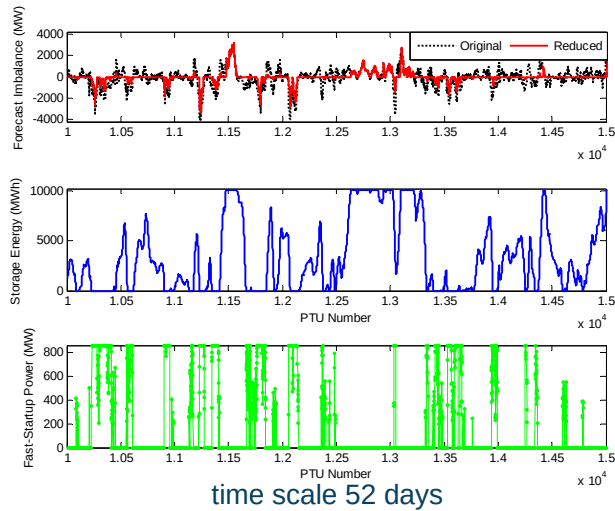


Analysed measures to reduce imbalance: 3. Pumped storage in combination with fast power units

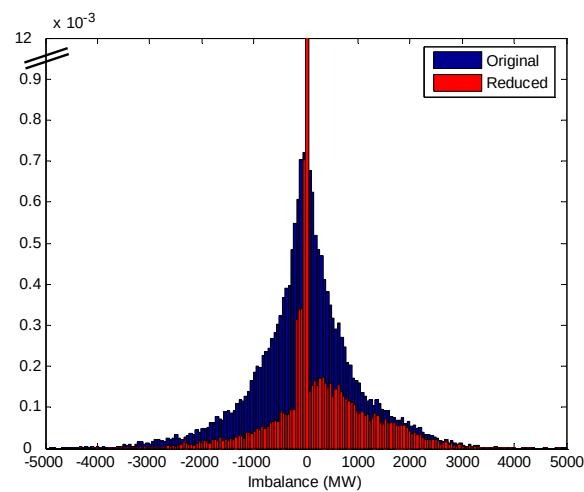
- A pumped storage (PS) system 1260 MW/ 10.08 GWh, (charging time 8 hours)
- A compressed air energy storage (CAES) system of 7.2 GWh (charging time 8 hours), with a 0.8 compression and a 1.4 charge efficiency factor, which means that the amount of energy that can be generated at full discharge is $7200 \times 1.4 = 10.08$ GWh
- Fast start-up units (852 MW) for reduction negative imbalance



Analysed measures to reduce imbalance: 3. Pumped storage in combination with fast power units



Pumped Storage & Fast Start-Up: Before and After Histograms



Analysed measures to reduce imbalance:

3. Pumped storage in combination with fast power units

	10080 MWh Pumped Storage	7200 MWh CAES	10080 MWh PS 852 MW Fast Start-Up
σ [p.u.]	0.84	0.84	0.66
μ^+ [p.u.]	0.61	0.68	0.61
μ^- [p.u.]	0.68	0.64	0.25
99.7% C.I. [MW]	[-3530..3310]	[-3421..3326]	[-2678..3310]

- Positive imbalance better reduced (due to pump efficiency of 0,9 → 111% more energy stored)
- Negative imbalance: only 90% of stored energy can be applied
- With fast power units → reduction up to 25 %!



Analysed measures to reduce imbalance:

4. Inverse Off shore Pump Accumulation system (IOPAC)

*Artificial Island in Nordsea:
Concept "Energy Island"*

~ 6 x 10 km



- A 40 meters deep dredged reservoir enclosed by a ring of dikes containing 2.000 MW / 30 GWh for Energy Storage
- Island can be made with the sand of the pit
- Space for ~ 500 MW of wind turbines
- Other forms of energy possible (eg biomass or tidal)
- Lokation for safety critical plants (eg LNG terminal)

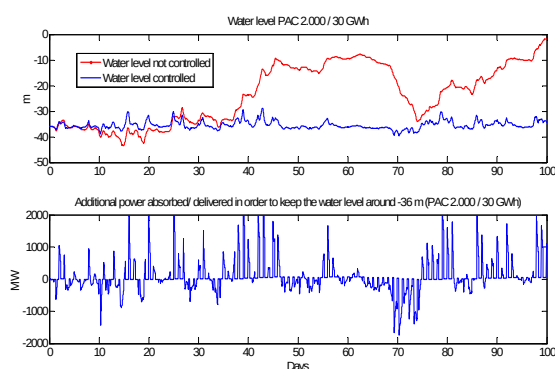




Artist impression



Analysed measures to reduce imbalance:
4. Inverse Off shore Pump Accumulation
system: 2.000 MW / 30 GWh



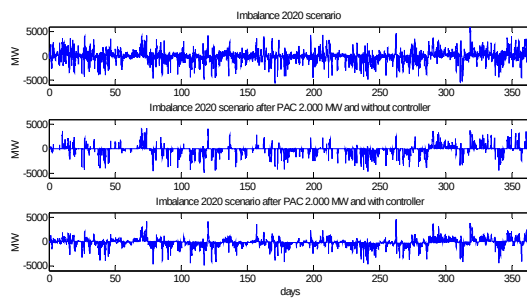
Water level drift away

Is controlled by
keeping storage
system in good
operating point by
selling from / buying to
market



Analysed measures to reduce imbalance:

4. Inverse Off shore Pump Accumulation system: 2.000 MW / 30 GWh



Imbalance

Imbalance after IOPAC, $\sigma = 0,714$

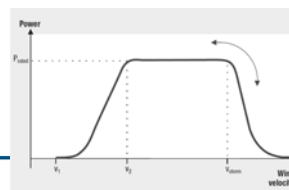
Imbalance after IOPAC +
market actions, $\sigma = 0,697$



Analysed measures to reduce imbalance:

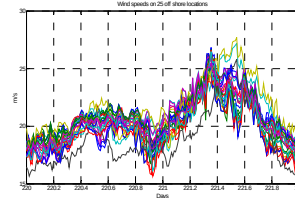
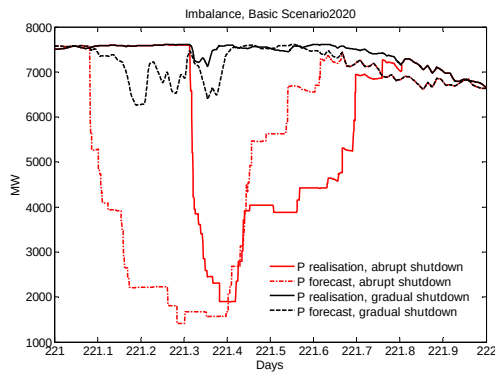
5. Shutting down strategies

- Incidental large imbalances were found due to forecast errors during storm fronts, ~5.000 MW forecast 12-36 hours ahead (with strategy 1)
- Shutting down Strategies analysed
 1. shutting down within 10 seconds if wind speed > 25 m/s, and is started up again within 10 seconds wind speed < 22 m/s.
 2. Gradual shutting down in dependence of wind speed



Analysed measures to reduce imbalance: 5. Shutting down strategies

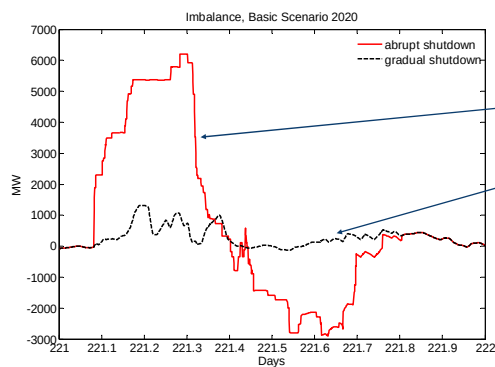
wind speed



Wind power realisation vs
forecast strategy 1 and 2



Analysed measures to reduce imbalance: 5. Shutting down strategies



Resulting imbalance
strategy 1 and 2



Conclusions analysed measures to reduce imbalance

Effect

- | | | |
|--|---|---|
| 1. Short term forecast | → | Strong, reduction imbalance up to 30% (3 hours ahead) |
| 2. Aggregation of forecast error | | Minor impact (~6% reduction of 99,7% confidence interval) |
| 3. Pumped storage in combination with fast power units | → | Up to 65% to 25 % reduction (given our dimensions of systems) |
| 4. Inverse Off shore Pump Accumulation system | | |
| 5. Shutting down strategies | → | A must and/or combined with forecast improvement |
-

Recommendations measures to implement NL

1. Short term forecast
2. Shutting down strategies
3. Aggregation of forecast error (if feasible)
4. Storage, if costs – benefits are acceptabel



Questions?

Thanks for attention!