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# Impact of Offshore Wind Power Variability on the Frequency Stability of European Power System

Nicolaos A. Cutululis \*, Marisciel Litong-Palima \*, Poul Sørensen \*

**Abstract** – Offshore wind power development scenarios are very ambitious. In Europe, it is expected to surpass 100 GW by 2030. As opposed to onshore, offshore wind will be concentrated in relatively small geographical areas, meaning that the geographical smoothening would be diminished. Being able to simulate this variability is important and will assist quantifying the possible impacts of large-scale deployment of offshore wind on the operation of the power system. The analysis of maximum offshore wind power ramping in 2020 and 2030 North Seas shows that wind power variability, at synchronous area level, can exceed the current dimensioning incidents values. This indicates that wind power variability should be considered in frequency stability.

**Keywords:** Offshore, Wind Power, Variability, Frequency stability

## 1. Introduction

Wind power is the most promising renewable technology and is expected to contribute significantly to achieving the “20-20-20” target set by EU - 20% reduction of greenhouse gases and 20% share of renewables by 2020 [1]. The development potential of wind power, especially offshore, is huge. For example, in Denmark only, the target is that wind power will supply approximately 50% of the electricity production by 2025. In order to achieve that, a large amount of offshore wind power, i.e. in the area of 2.5 GW, will be installed in North Sea, in sites that have been selected and published by the Danish Energy Authority [2].

The TWENTIES project ([www.twenties-project.eu](http://www.twenties-project.eu)) aims at “demonstrating by early 2014 through real life, large scale demonstrations, the benefits and impacts of several critical technologies required to improve the pan-European transmission network, thus giving Europe a capability of responding to the increasing share of renewable in its energy mix by 2020 and beyond while keeping its present level of reliability performance” [3]. The Storm Management demonstration’s objective is: “The occurrence of storms will raise new challenges when it comes to secure operation of the whole European electric system with future large scale offshore wind power. With the present control schemes, storms will lead to sudden wind plant shut downs, which in turn is a threat to the whole system security, unless standby reserves are ready to take over power demands under very short notice. The challenge that this demonstration is addressing

is to balance the wind power variability, operating the transmission grid securely during such storm conditions. The more specific objectives of the demonstration are to:

- Demonstrate secure power system control during storm passage, using hydro power plants in Norway to balance storm shut down of Horns Rev 2 wind farm in Denmark.
- Use existing forecast portfolio available to the TSO to monitor and plan the down regulation of large scale offshore wind power during storm passages.
- Provide more flexible wind turbine and wind farm control during storms.” [3].

The demonstration is performed on a single offshore wind farm. In order to quantify the offshore wind power variability by 2020 and 2030, simulations are used.

The paper presents the results of the analysis of the offshore wind power variability, in 2020 and 2030, in North Europe. The next section presents the simulation tools used in the analysis, followed by the simulation scenarios and the results. Finally, a conclusion section ends this paper.

## 2. Simulation tools

### 2.1 CorWind

The analyses presented in this report are based on simulations with the CorWind power time series simulation model developed at DTU Wind Energy [4]. CorWind can simulate wind power time series over a large area such as a power system region and in time scales where the wind turbines can be represented by simple steady state power curves, i.e. typically greater than a few seconds. CorWind can be used e.g. for comparison of the impact of the site

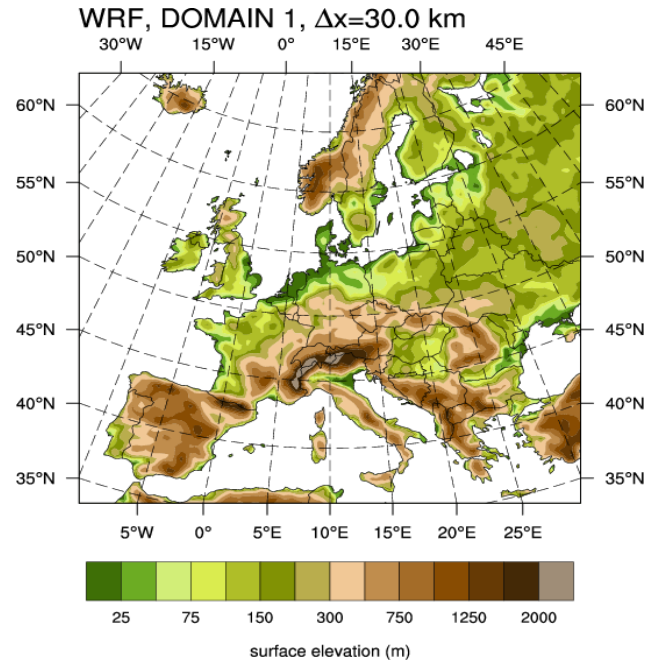
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selection of future wind farms on the system reserves requirements.

The CorWind is an extension of the linear and purely stochastic PARKSIMU model [5], which simulates stochastic wind speed time series for individual wind turbines in a wind farm, with fluctuations of each time series according to specified power spectral densities and with correlations between the different wind turbine time series according to specified coherence functions. The coherence functions depend on frequency and space, ensuring that the correlation between two wind speed time series will decrease with increasing distance between the points. Moreover, the slow wind speed fluctuations are more correlated than the fast fluctuations. Finally, the stochastic PARKSIMU model includes the phase shift between correlated waves in downstream points, ensuring that correlated wind speed variations will be delayed in time as they travel through the wind farm. These model properties ensure that the summed power from multiple wind turbines will have realistic fluctuations, which has been validated using measured time series of simultaneous wind speeds and power from individual wind turbines in two large wind farms in Denmark [6].

The CorWind extension of PARKSIMU is intended to allow simulations over a large areas and long time periods. The linear approach applied in PARKSIMU assumes constant mean wind speeds and constant mean wind directions during a simulation period, which limits the geographical area as well as the simulation period significantly – typically to the area of a single wind farm and to max 2 hours periods. CorWind uses reanalysis data from a climate model to provide the mean wind flow over a large region, and then adds a stochastic contribution using an adapted version of the PARKSIMU approach that allows the mean flow to vary in time and space.

The meteorological data come from a climate simulation using the Weather Research and Forecasting (WRF) model and the dynamical downscaling technique developed by Hahmann et al [7], but using Newtonian relaxation terms toward the large-scale analysis (also known as grid or analysis nudging). Initial and boundary conditions and the gridded fields used in the nudging are taken from the NCEP reanalysis [8] at  $2.5^\circ \times 2.5^\circ$  resolution. The sea surface temperatures are obtained from the dataset of Reynolds et al [9] at  $0.25^\circ$  horizontal resolution and temporal resolution of 1 day. The simulation covers the period from 1 January 1999 to 31 December 2010 with hourly outputs. The model is integrated within the domain shown in Fig. 1.



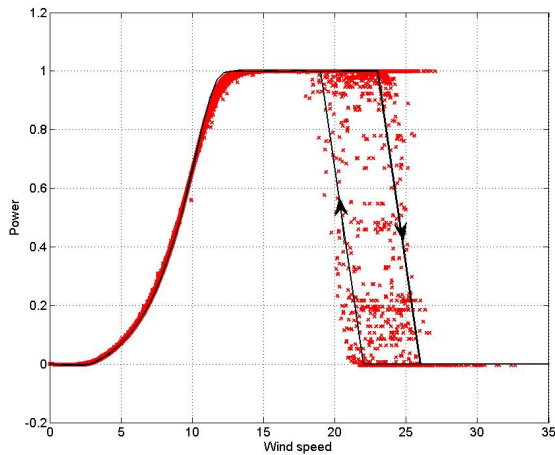
**Fig. 1.** Domain configuration and terrain elevation used in the simulations for domain (30 km).

## 2.2. Wind2Power module

The Wind2Power module does, as the name suggests, the conversion from wind speed to power. This conversion can be done using the so-called power curve, which is the characteristic curve that describes the relationship between the wind speed and power. In this study, our interest lies in simulating the power production in the synchronous areas in Northern Europe for all the probable values of the wind speed, from the low level all the way up to the high level, i.e. during storms. Before we can do this, we first needed to validate our tools at the turbine and at the farm levels.

The power curve is given for a single wind turbine hence using it directly implies simulating each individual wind turbine, in each simulated wind power plant. This is achievable when the focus is on one or few wind power plants, summing up to a few hundreds wind turbines. In this work, the focus is on the entire North Europe and to an installed capacity of more than 140GW in the 2030 scenario, divided across almost 400 wind power plants [10]. This meant that it was needed to derive an aggregated wind power plant power curve. The exercise started with a generic 200MW wind power plant power curve available at DTU Wind Energy and validated against measurements from Horns Rev 2 wind power plant in Denmark [11]. The Wind2Power module of CorWind is then updated to run the two cases of storm control. After this validation,

CorWind is used to estimate the aggregated power curve for Horns Rev2, as shown in Fig. 2



**Fig. 2.** Estimation of the aggregated power curve for Horns Rev 2 using CorWind with the Wind2Power module

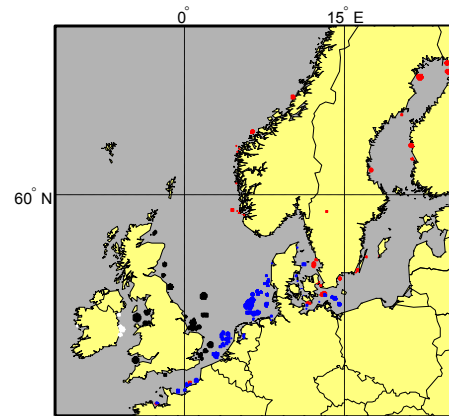
### 2. Simulation Scenarios

The analysis aimed at quantifying the variability of offshore wind power in 2020 and 2030. For that, the simulations used the wind power development scenarios from the TWENTIES project [5]. The database created includes the coordinates of the wind farms. The total number of wind farms considered is 379 for 2030. The MW installed capacities, per considered power system areas, are given in Table 1.

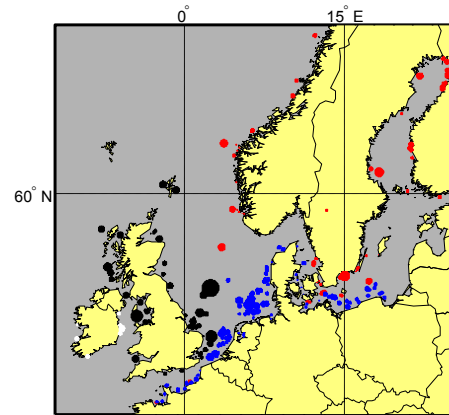
**Table 1.** Wind power capacities considered in the scenarios, per synchronous areas

Power System Areas	2020 in MW	2030 in MW
	Base	Base
Continental	21,421	54,187
Nordel	4,913	14,798
GB	13,711	33,601
Ireland	1,419	4,319

The geographical distribution of the offshore wind farms considered in the analysis is shown in Figure 1 for 2020 and in Figure 2 for 2030, respectively. The circles are scaled with the installed capacity.



**Fig. 3.** Offshore wind farms per synchronous system – 2020 (Continental – blue, Nordic – red, GB – black and Ireland – white)



**Fig. 4.** Offshore wind farms per synchronous system – 2030 (Continental – blue, Nordic – red, GB – black and Ireland – white)

In the analysis, a total of eight meteorological (or wind speed) years were used in the simulations. The selection was done taking into account the existence of data, the number of very high wind events recorded and the need of different, i.e. “good” or “average”, etc, wind years. In the following, we refer to the years as Meteo Years from 1 to 8. Their correspondence with calendar years is given in Table 2.

**Table 2.** Correspondence between meteo and calendar years

Meteo Year	Calendar Year
1	2001
2	2005
3	2007

4	2008
5	2009
6	2010
7	2011
8	2012

#### 4. Maximum ramping

The definition of maximum ramping applied in this report is quite similar to the definition of regulation applied in [5] and used in [6]. The intention is to define a quantity which can be used to assess if the frequency stability is threatened due to sudden (or short term) loss of wind power generation.

In order to quantify the short-term loss of wind power generation, the maximum ramping is defined as the difference between the present power and the minimum instantaneous power in the following time window  $T_{win}$ . Since the reserves must be allocated in advance, the positive reserve requirement is defined as the difference between the initial mean value and the minimum value in the next period. It has also been chosen to use a mean value of the present power rather than an instantaneous value with average periods  $T_{ave}$ , because the initial value is rather random. The assessment of maximum ramp rates is involving a statistical window time  $T_{win}$ , which reflects the time scale of interest. The time scales of interest will depend on the power system size, load behavior and specific requirements to response times of reserves in the system. In order to study the wind variability in different time scales, the analysis is performed for several time windows. In this analysis, the time scale of interest is 15 minutes, meaning that in the rest of the report, when maximum ramping is used,  $T_{win} = 15$  minutes.

This definition of maximum ramping is illustrated for time windows  $T_{win} = 60$  min and average periods  $T_{ave} = 15$  min in Fig. 5. The simulated (or measured) instantaneous power is shown in gray tone. The mean values for the latest 15 min are calculated and shown in black. For each 15 minute period, the reserve requirement is calculated as indicated by the arrows.

$$P_{res}(n) = P_{mean}[t(n) - T_{ave}; t(n)] - P_{min}[t(n); t(n) + T_{win}]$$

Here,  $[t_{beg}; t_{end}]$  denotes the time period from  $t_{beg}$  to  $t_{end}$ . Note that with this definition, positive ramping means decreasing wind power that requires positive ramping from other power plants

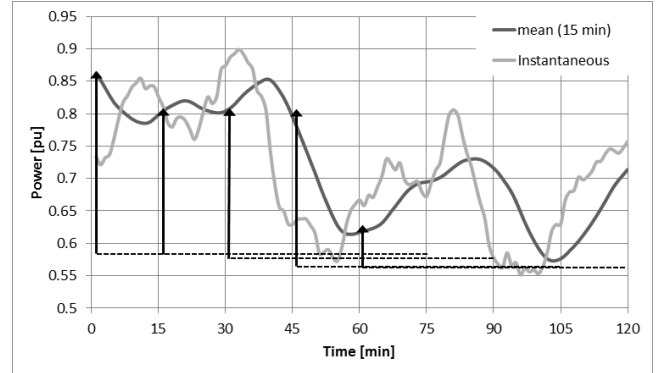


Fig. 5. Definition of maximum ramping

#### 5. Results

The frequency stability in a synchronous power system area relies on the availability of sufficient online frequency containment (also called spinning) reserves to handle unexpectedly lost generation in the first instance. In the Continental European synchronous area, the reference incident is defined as the loss of 3,000 MW generation [12]. The corresponding dimensioning outage is 1,200 MW in the Nordic Synchronous area [13]. For GB and Ireland, the values considered in this paper are 1,800 and 500 MW respectively.

In the second instance, the frequency containment reserves must be replaced by frequency replacement reserves, so that normal security level is re-established within a certain time. This reserve replacement usually takes up to 15 minutes, and additional loss of generation within this time period can cause frequency stability problems.

Normally, the need for frequency containment reserves is set so that the frequency remains stable after loss of the largest generation unit. However, the frequency stability can also be threatened if the wind power generation drops with more than the online frequency containment reserves within 15 minutes. This is normally not an issue because the total wind power changes relatively slow over large areas, but in case of a storm passage with massive scale offshore wind power concentrated in relatively small areas, the wind power generation can drop significantly within 15 minutes.

The maximum ramping, is giving an image of the required spinning reserve – of course not detailed, as this would depend on a number of other parameters besides wind power production. In the following, the results of the maximum ramping for each synchronous area for 2020 and 2030 are given.

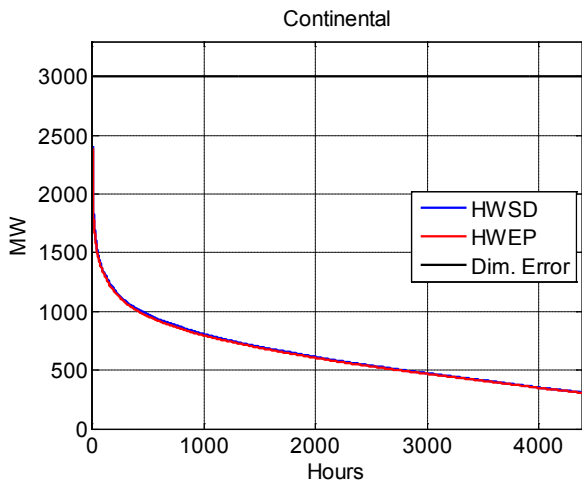


Fig. 6. Fifteen minutes maximum ramping duration curve for the Continental area in 2020

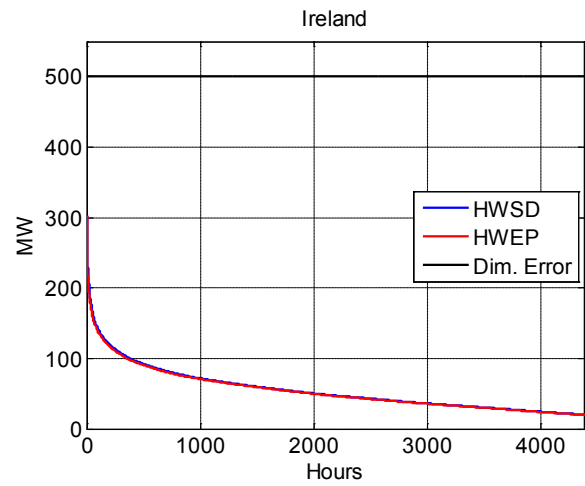


Fig. 9. Fifteen minutes maximum ramping duration curve for the Irish area in 2020

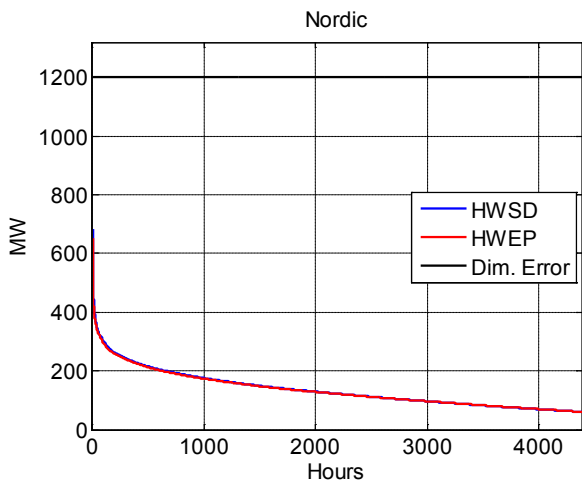


Fig. 7. Fifteen minutes maximum ramping duration curve for the Nordic area in 2020

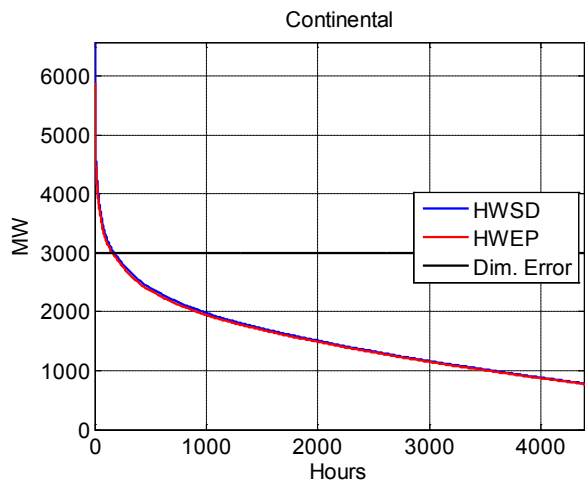


Fig. 10. Fifteen minutes maximum ramping duration curve for the Continental area in 2030

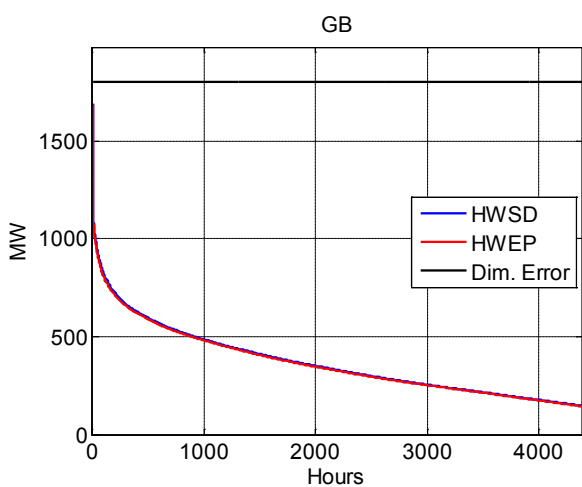


Fig. 8. Fifteen minutes maximum ramping duration curve for the Great Britain area in 2020

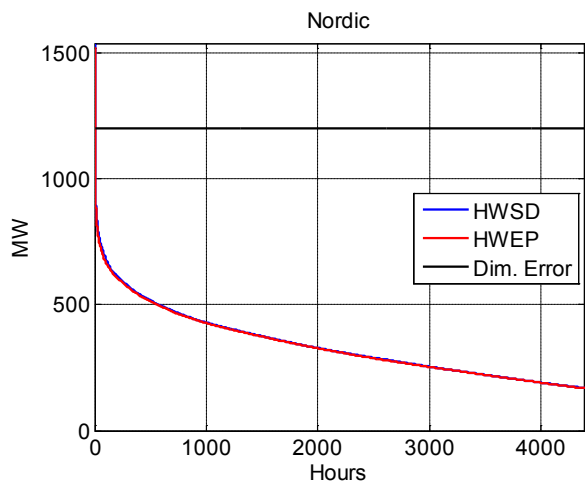


Fig. 11. Fifteen minutes maximum ramping duration curve for the Nordic area in 2030

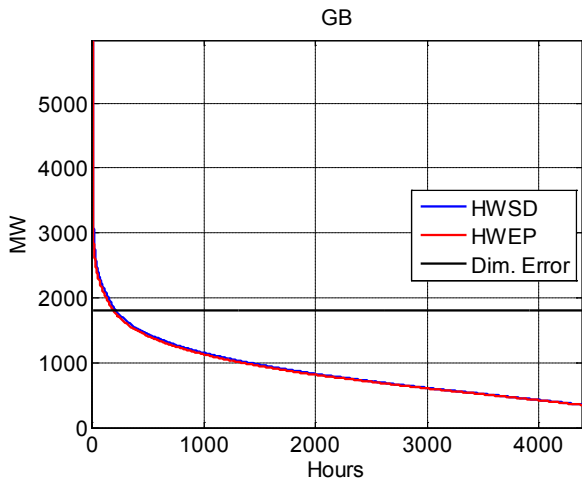


Fig. 12. Fifteen minutes maximum ramping duration curve for the Great Britain area in 2030

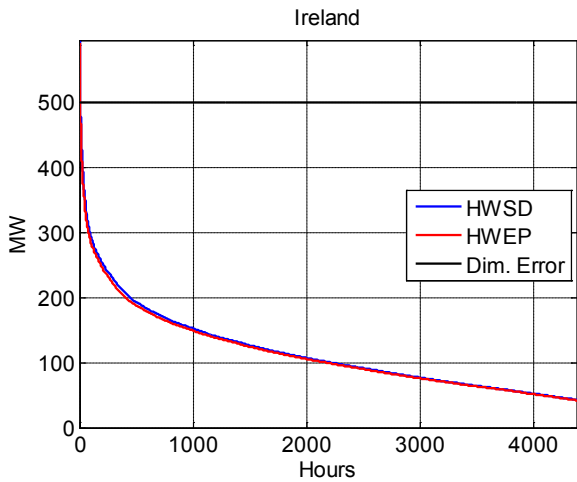


Fig. 13. Fifteen minutes maximum ramping duration curve for the Irish area in 2030

Table 3 Highest values of wind power ramping vs reference incident, 2020 scenario

Synchronous area	HWSD [MW]	HWEP [MW]	Reference [MW]
Continental	2,413	2,391	3,000
Nordic	684	652	1,200
GB	1,691	1,687	1,800
Ireland	302	302	500

Table 4 Highest values of wind power ramping vs reference incident, 2020 scenario

Synchronous area	HWSD [MW]	HWEP [MW]	Reference [MW]
Continental	6,571	2,391	3,000
Nordic	1540	652	1,200
GB	5,972	5,992	1,800
Ireland	595	591	500

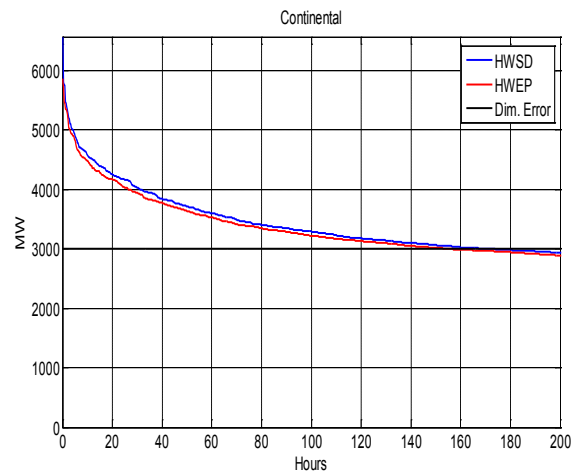


Fig. 14. Hours when max ramping exceeds reference incident, Continental system, 2030

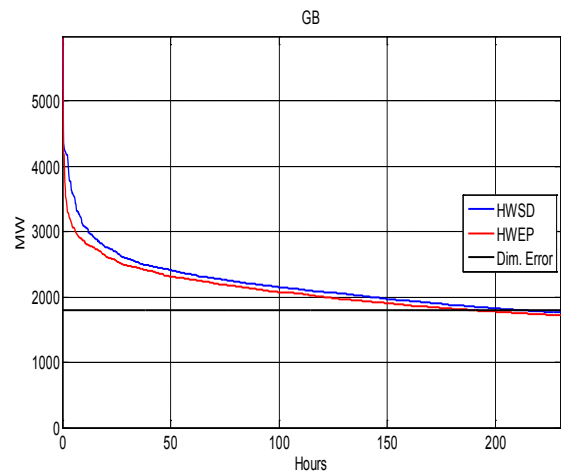


Fig. 15. Hours when max ramping exceeds reference incident, Nordic system, 2030

For the 2030 scenario, the highest value of the maximum ramping is exceeding the reference incident for all areas considered, with the values of Continental and GB systems being more than double that. The number of hours when the maximum ramping is exceeding the reference incident can be seen in Fig. 14 and Fig. 15, for the Continental and GB system, respectively. For the Nordic and Irish system the number of hours is very small.

## 5. Conclusion

Analysing the variability of wind power in the four synchronous systems considered revealed that, for 2020, wind power maximum ramping – while significant at times – it does reach values higher than the current dimensioning incidents values. For the 2030 scenario, this is not the case, with the values exceeding – for some systems significantly – the dimensioning incidents values. This indicates that the offshore wind power variability should be considered in frequency stability assessment. This work has not been analysing how this should be done, but one way could be to introduce a variable requirement for frequency containment reserves, depending on the current wind power production.

## Acknowledgements

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