# OFFSHORE INTEGRATION STUDY

Analysis, benchmark and mitigation of storm and ramping risks from offshore wind power in Belgium

05/02/2018

This study has been developed in close collaboration with

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# EXECUTIVE SUMMARY

A significant increase of the offshore wind production is expected up to 2020 in the Belgian offshore area. Once all offshore parks will be fully operational the total installed capacity will increase to 2300 MW. The unexpected variations in wind farms power production due to high wind speed (hereafter also defined as "storm event") or sudden changes in wind power or direction (hereafter also defined as "ramping event") might at that time trigger **substantial imbalances** in the Belgian control area.

Furthermore, because all Belgian offshore wind parks are situated close to each other in the North Sea, it has been observed that they all behave in a similar way facing a storm or ramping event and that impact will mainly differ because of wind turbine technical characteristics (a.o: the wind speed cut out which corresponds to the technical limit from which a wind turbine stops producing because of too high wind speeds (protection mode)).

To better understand the **possible impact of storm and ramping event on ELIA's control area (balancing risk)** in order to elaborate – if the need is confirmed - an adequate implementation plan for the coming years, ELIA initiated this study with the help of the external company 3E. This document presents the results of the statistical assessment realized on observed events in 2015 and 2016, the extrapolation towards installed capacity in 2020 and formulates recommendations. It is important to mention that this study does not cover scenarios where offshore installed capacity increases beyond 2300 MW nor proposes solutions for situations where wind production exceed the consumption (as it becomes the case in Denmark).

**Statistical assessment of storm and ramp events (observed over the period Sept. 2015- to Dec. 2016)**

<u>Storm events</u>

Storm event can be categorized in 3 groups in function of the observed impact of a storm event as summarized in table 1 below. **In total, 16 storm events are identified over the period studied**.

| Storm category | Definition | 2016 installed capacity concerned for each storm category (MW) | Average power loss (MW) measured per storm category | Average power loss (%) measured per storm category | # of storm event observed |
|---|---|---|---|---|---|
| Small | partial cut out on wind parks with cut out limit at 25 m/s | 386 | 166 | 43,01% | 7 |
| Moderate | full cut out on wind parks with cut out limit at 25 m/s | 386 | 355 | 91,97% | 8 |
| major | full cut out on both wind parks with cut out limit at 25 m/s and 30 m/s | 712 | 656 | 92,13% | 1 |

*Table 1 – Storm categorization*

Furthermore, looking at the results of this statistical assessment, 4 important conclusions can be drawn:

1. In a majority of storm events ("moderate" and "major"), the **average power loss following a storm is above 90 % of the installed capacity** of wind parks concerned by these categories;

2. **Cut-in duration** (once the wind parks start producing again following a cut out due to a storm event) **is on average faster than the cut out duration**.

3. Both storm duration (from start of cut out phase until end of cut in phase) and cut in or cut out **durations are very volatile from one event to the other**.
4. All events observed occurred in fall and winter time (between September and March).

Ramping events

To investigate ramp impact on ELIA's control area, several power variation (150 MW, 300 MW, 450 MW and 600 MW) and timeframe (7.5 min, 15 min, 30 min and 60 min) are considered. In 2016, their occurrences (and therefore impact on ELIA's control area) are limited due to the relatively low installed offshore capacity.

**Results extrapolation with expected installed offshore capacity in 2020**

Storm events

At the time of this study, it is expected to have an additional 1414 MW in operation in 2020 (6 additional wind parks). Because the cut out wind speed threshold is not confirmed yet for those parks and considering the market evolution observed over the last years, ELIA determined 4 different scenarios to extrapolate the results to 2020. The worst case scenario (Scenario A) considers that each new wind turbine is equipped with a cut out limit of 25 m/s while in the best case scenario (Scenario D) all this additional capacity is equipped with more recent cut out technologies (with smoother power decrease between 25 m/s and 32 m/s).

The table 2 below summarizes most important results for each scenario, per storm category.

| storm category | Power loss (MW)- scenario A | | | Power loss (MW) - scenario B | | | Power loss (MW) - scenario C | | | Power loss (MW) - scenario D | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | min | max | average | min | max | average | min | max | average | min | max | average |
| small | 622 | 1062 | 812 | 413 | 965 | 576 | 237 | 522 | 372 | 176 | 308 | 241 |
| moderate | 1548 | 1806 | 1393 | 1048 | 1638 | 1333 | 449 | 1476 | 960 | 463 | 547 | 505 |
| major | 2144 | | | 2143 | | | 2136 | | | 2131 | | |

*Table 2 - Power loss per storm category and scenario in 2020*

It can be concluded that in most realistic scenarios (B & C) the power loss caused by a storm event often goes beyond 1000 MW while a major event will always cause a power deviation of more than 2000 MW.

Finally, looking at the maximal ramps observed in both cut out and cut in phases, it is observed that deviations around 1000 MW can happen in both directions (up and down) within 30 minutes.

Ramping events

When extrapolating to 2020, the occurrences of ramps become more significant. On average, power variation of 150 MW within 15 minutes will happen around 3 % of the time.

**Forecastability of storm and ramping events**

To determine how accurately the storm and ramp events were predicted based on data made available by ELIA, several methodologies are investigated. The results clearly highlight the advantages of the forecast method based on wind speed forecasts.

Furthermore, a significant deterioration in the results is observed as soon as we consider a forecast horizon different than the intraday (ex: day ahead). Finally, looking more specifically into all moderate and major storm events, it is concluded that all the observed events were identified in most recent update of the wind speed forecasts. Only in 3 cases did the forecast of a storm event not led to an “observed” storm (false positive).

Regarding ramping events, none of the methodologies investigated led to qualitative results.

**Benchmark with 5 other European countries**

5 European countries were studied to determine if the balancing risk caused by Belgian offshore configuration is also relevant for their respective TSO. TenneT (Netherlands), 50Hertz (Germany) as well as National Grid (UK) and SVK (Sweden) reported that the effect of storms and ramping events on their offshore wind parks are negligible because of the low impact of the wind installed capacity compared to their load as well as their geographical repartition.

On the contrary, the fifth TSO, Energinet (Denmark) must deal with 5 GW of wind installed capacity while peak demand is only of 6.1 GW. As a consequence, specific measures are defined in their technical regulation to cope with **situations where production goes beyond consumption**.

Energinet faces a different risk than the one detected for Belgium. The two main differences are that the offshore parks in Denmark are geographically spread around the country which significantly reduces the balancing risk caused by storm events and that Belgium does not face yet situations where wind production overtakes its load (considering the installed offshore capacity of 2300 MW used as assumption for this study).

**Recommendations**

<u>Storm events</u>

Two major axes for improvements are identified based on results obtained in this study:

1) Development of specific storm forecast model

A specific storm forecast model should be developed by ELIA to better manage the balancing risk caused by a storm. This model must be calibrated **with wind speed measurements (historical and real time data) taken at strategic locations and height of the offshore wind turbines to deliver the best forecast possible**. This will allow ELIA to implement and apply specific operational procedures.

Furthermore, because not all storm events can be forecasted, ELIA must also increase its monitoring of **offshore production in real time** to detect as soon as possible an on-going storm event.

2) Re-inforce operational procedures between BRPs and ELIA to better coordinate mitigation actions in reaction to a storm event

Based on the outcome of ELIA's storm model (published on ELIA's website) and in collaboration with BRPs responsible for offshore wind production, ELIA will implement specific **operational procedures** to better **coordinate BRP's actions** in reaction to a positive storm forecast.

Four different new procedures will be elaborated:

A. As soon as a coming storm is detected, BRPs responsible for offshore production will confirm to ELIA which kind of **mitigation measures they foresee** to cover the expected power decrease on offshore parks subject to the storm.

B. For moderate storm events, in real time (at storm occurrence) and as back-up solution in cases BRPs cannot apply their mitigation measures as expected ELIA may take the decision to trigger its exhausted reserve process"[1] to reduce the storm impact on its control area and/or limit in time the use of its balancing reserves.

C. For very specific situations triggered once the forecasted storm impact (MW) exceeds ELIA's regulation means[2] and in coordination with involved offshore BRPs ELIA may start this exhausted reserve process several hours in advance in anticipation to the major impact caused by this storm category.

D. Before restarting their offshore wind production, BRPs[3] will take contact with ELIA to communicate all operational details (e.g: timing proposal to start producing again, ramps applicable…) related to the come-back of offshore park to its initial production level. Based on this information ELIA will analyse if the come-back can be realized as scheduled and confirm the proposed planning to the BRP. In any cases, all BRPs must respect the maximal ramp rate constraint set by ELIA in the "LFC Bloc agreement" once it enters into force.

Ramps events

An additional analysis must be performed by ELIA to determine if specific meteorological parameters could be used in some ways to forecast most important ramp events.

[1] The elaboration of the **exhausted reserve process** is part of the scope of the "LFC Bloc agreement", a document that will be written by ELIA and submitted to consultation in 2018 as required by the System Operation Guidelines.

[2] ELIA's regulation means are calculated following a dimensioning methodology periodically subject to public consultation and to regulator's approval.

[3] The operational and contractual implementation including determination of roles and responsibilities are subject to further analysis

# 1. Introduction

Up to 2020 a significant increase in the offshore wind production is expected in the Belgian North Sea. Once all offshore parks will be fully operational the total installed capacity will reach 2292 MW (compared to 712 MW at the period of reference used by this study (2016)).

Furthermore, as illustrated by the map presented in the figure below, all Belgian offshore wind parks will be situated close to each other in the North Sea. With this specific configuration, similar production behaviour in case of important wind speed changes have been observed in the past, the differences coming only from the wind turbine cut out wind speed limit (the wind speed from which a turbine stops producing because of too high wind speed (physical / technical limit of the equipment).

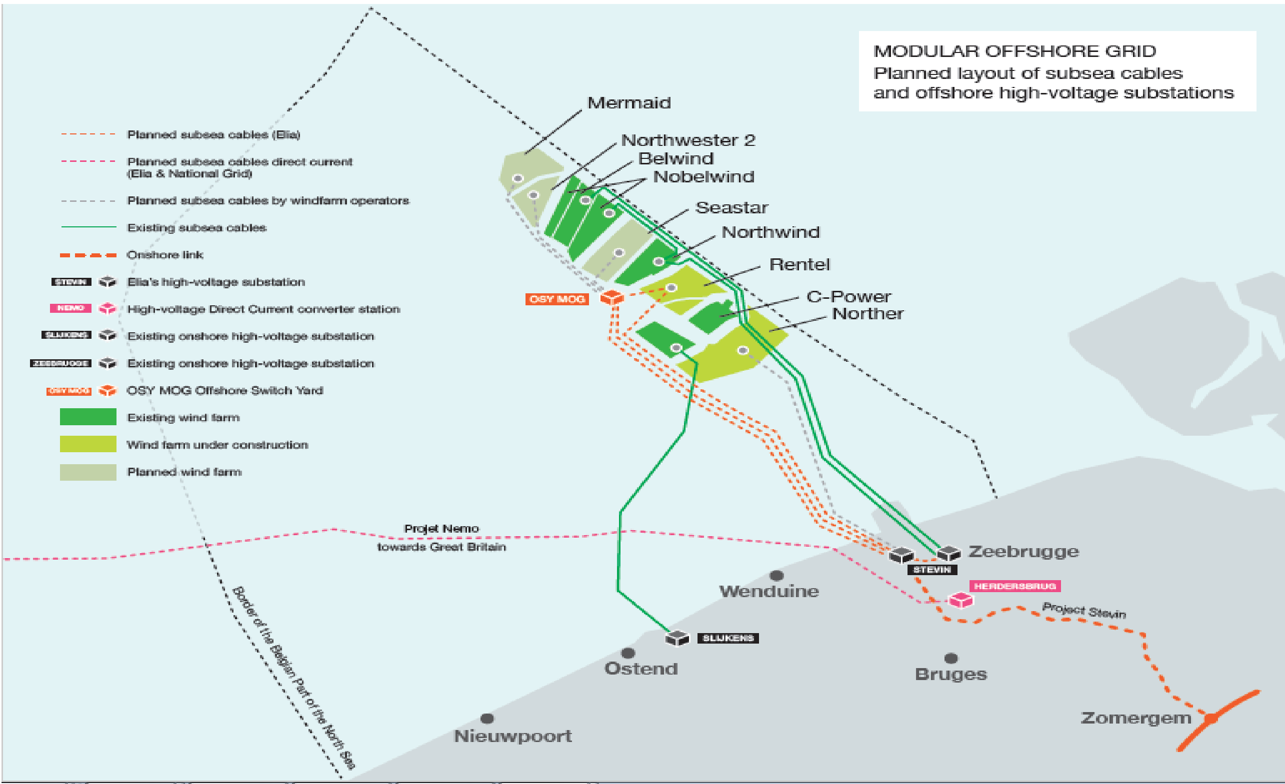


*Figure 1 - Belgian offshore configuration (status 27/11/2017)*

Elia is concerned about possible impact of unexpected variations in wind farms power production due to high wind speed (hereafter also defined as “storm events”) or sudden changes in wind power or direction (hereafter also defined as “ramping events”) ”) on the balancing performance of BRPs and hence the residual imbalance to be resolved by Elia. To better understand offshore parks behaviour in these specific meteorological conditions, ELIA initiated this study with the help of the external company 3E.

> <u>Disclaimer</u>
>
> This study focuses on the offshore configuration for 2020 whereas 2.3 GW will be installed. In case this installed capacity continues to increase in the years to come ELIA might need to consider additional measures, on top of those presented in this document.

This study is organized in 6 chapters. The first chapter summarizes all the data used by 3E and ELIA in the analysis presented in this document.

The second chapter presents an historical analysis of storm and ramp events. This chapter includes a description of the methodology followed by 3E and ELIA and a description of the obtained results.

In the third chapter, an extrapolation towards 2020 is done by ELIA and 3E based on the results of the historical analysis and the expected future installed offshore capacity. Because the technical characteristics of the new parks (a.o the cut out wind speed limit) are not known to ELIA at the moment of this study, several scenarios are elaborated to cope with this uncertainty.

In the fourth chapter, 3E and ELIA analyse the accuracy and reliability of several methodologies to predict storm and ramping events.

In the fifth chapter a benchmark is performed regarding the storm mitigation actions (if any) implemented in 5 other European countries. The objective is to determine whether the risk identified by ELIA is also applicable to other countries and when relevant learn from solutions which have been implemented (if any). This benchmark has been realized by 3E.

Finally, the last chapter summarizes ELIA’s recommendations.

# 2. Data used by 3E and ELIA in this study

## 2.1. Data sources

The analysis of storm and ramp impact on offshore wind production in Belgium is performed based on historical time series data related to wind speed and offshore production. The different data sources used by 3E and ELIA in this study are presented below:

### INSTALLED OFFSHORE CAPACITY

At the moment of this study, ELIA disposes of the following information on the evolution of offshore installed capacity until 2020:

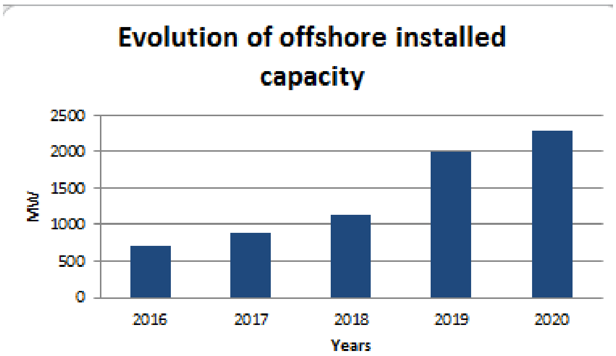


*Figure 2 – Evolution of offshore installed capacity between 2016 and 2020*

In 2020, if all new parks are connected as planned today (Q4 2017), there will be 2292 MW of installed capacity (1996 MW in 2019). This is the reference used in all extrapolations calculated in this study. No scenarios considering additional installed offshore capacity beyond 2020 are investigated here.

### MINUTE PRODUCTION MEASUREMENTS OF CURRENT OFFSHORE PARKS

At the moment of the study, 3 offshore wind parks are operational: Northwind, Belwind and C-Power. For these 3 parks, ELIA provided to 3E minute measurements of power production over the period Sept. 2015 – Dec. 2016.

### WIND PRODUCTION FORECASTS

Since 2011, ELIA publishes wind production forecasts on its website (http://www.elia.be/en/grid-data/power-generation/wind-power). They are provided for the next 7 days with an intraday update frequency of 4 times / day. These forecasts are the results of a combination of **weather** and **statistical** models provided by an external company specialized in these calculations.

An example of wind forecast for offshore wind farms is provided in the figure 3 below:

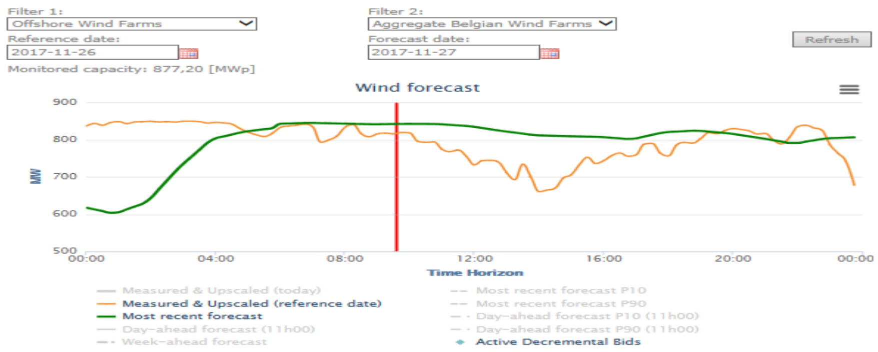


*Figure 3 - example of wind production forecast published by ELIA and updated four times per day*

### METEOROLOGICAL DATA (3E)

3E has complemented ELIA's provided wind data with two additional data sources. The first data source consists of MERRA data for 2012 – 2016. MERRA data (short for 'Modern Era Retrospective-Analysis for Research and Applications') is hourly forecasting and calibration data of NASA's Global Modelling and Assimilation Office, and the nearest available grid point - *i.e.* 51.5N 2.5E - at a 50 m height is considered.

The second data source is in-house LIDAR data of 3E with a time resolution of 10 minutes. These measurements were performed at a height of 100 meter on the Oostdijkbank Radar Platform between August 2011 and January 2013.

### HISTORICAL WIND SPEED MEASUREMENTS

ELIA also obtained 16 years of historical wind speed measurements from the Flemish hydrography (kust afdeling). The measurements were taken in the North Sea[4] at a height of 26.1 m with a time resolution of 10 minutes. In addition to the wind speed measurements, ELIA got over the same period the data on average wind direction (°) with the same 10 minute resolution.

To ease the reading of this report, each new chapter will start with the identification of the data used to get the results presented.

## 2.2. Data quality analysis

The historical wind speed measurements provided by ELIA are the most recent and detailed data available (on the longer period of time) at the moment of this study. All simulations and calculations performed in this study are therefore based on these measurements.

However, because these historical wind speed measurements were taken at a height of 26 meter (while an offshore wind turbine is built at a height around 100 m) and not at the exact same location, 3E verified its quality with 2 additional meteorological data: MERRA data and LIDAR data.

[4] Exact location of the measuring pile: N51°23'18.74'' E02°26'18''

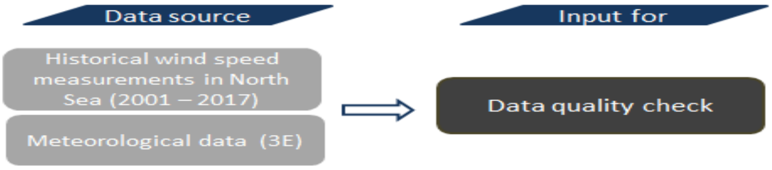


*Figure 4 - Data used for the data quality check*

Comparing these available sources of information, 3E calculated the impact of having different altitudes on wind speed measurements. In this way, an offset of 4 m/s is observed between wind measurements taken at 26 m and 100 m height.

Therefore, a margin of +- 4 m/s will be included in provided historical wind speed measurements when used as input to assess the frequency of storm events in 2015 – 2016. The use of this margin does not affect the quality of this historical analysis as a storm event is only identified in case a combination of high wind speeds and a significant drop in offshore power production is observed.

Although the absence of wind speed measurements at the right height is not affecting the study results, **it is crucial in the future that Elia receives wind speed measurements at the right height** to optimally develop specific operational processes (if needed) and improve its weather forecasts specifically for the detection of storm events (see also chapter 5) .

# 3. Statistical assessment of historical storm and ramping events

This chapter is made of 3 sections. In the first one, ELIA and 3E give a definition of the different elements studied in this study. In the next 2 sections, an assessment of the magnitude and frequency of respectively storm and ramping events in the past is performed.

## 3.1. Relevant definitions

**Storm event:** The storm event is defined by a cut-out and a cut-in phase. It is observed when the wind speed measurements reaches the technical threshold (cut out wind speed limit) of the wind turbine **AND** the power generated by this wind turbine decreases in consequence.

**Cut-out phase (hereafter cut-out):** the power loss not caused by wind speed decrease observed on wind parks during a storm event;

**Cut-in phase (hereafter cut-in):** the power generated following a cut-out phase from its start until the highest production rate.

**Cut out wind speed limit:** the technical threshold from which a wind turbine stops producing because the equipment's limit is reached. At the moment of this study, 2 wind parks have a cut out wind speed limit of 25 m/s and the third park has a cut out wind speed limit of 30 m/s.

**Storm event duration:** Duration from the moment the start of a cut-out phase is observed until the end of the cut-in phase.

**Maximal ramp:** the most significant power variation (loss or gain) measured in a certain period of time during the cut out and the cut in phase. Please note this does not correspond necessarily to the first minutes of the cut-out or cut in phase.

**Ramping event:** rapid power loss (or gain) observed in a certain period of time. This power variation is caused by a wind speed fluctuation.

These definitions are illustrated with the example presented in the figure 6 below:

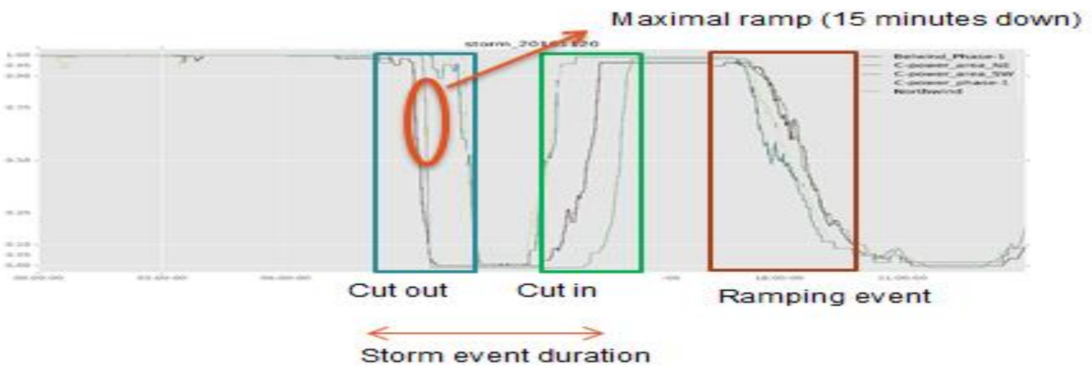


*Figure 5 - Concrete example of cut out, cut in, storm and ramp definitions based on the storm that occurred on 20/11/2016.*

## 3.2. Statistical analysis of storm events

To obtain the results presented in this section, 3E used the following data:

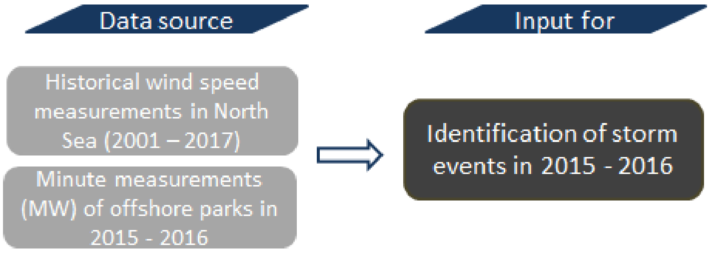


*Figure 6 – data used for the statistical analysis of storm events*

### Historical events

Taking the margin calculated in section 2.2 (needed because of the difference in altitude between the wind turbine and the wind speed measurements) into consideration, 3E identified 16 storm events over the period from September 2015 to December 2016, looking at the power curves calculated for each offshore wind park, and calculated several statistical indicators.

From this statistical analysis, it is possible to categorize storms in 3 categories: small, moderate and major. The table 3 below summarizes information on each storm category, considering 2016 installed offshore capacity (712 MW):

| Storm category | Definition | 2016 installed capacity concerned for each storm category (MW) | Average power loss (MW) measured per storm category | Average power loss (%) measured per storm category | # of storm event observed |
|---|---|---|---|---|---|
| Small | partial cut out on wind parks with cut out limit at 25 m/s | 386 | 166 | 43,01% | 7 |
| Moderate | full cut out on wind parks with cut out limit at 25 m/s | 386 | 355 | 91,97% | 8 |
| major | full cut out on both wind parks with cut out limit at 25 m/s and 30 m/s | 712 | 656 | 92,13% | 1 |

*Table 3 - categorization of storm events*

For the 8 most significant (moderate and major) storm events, the **loss of power** caused by the event **is on average beyond 90 % of the installed capacity**.

Partial cut out observed in small storm category can be explained by multiple factors:

- Only one out of the two existing parks cuts out while the other keeps producing due to small difference in the actual set threshold value or different observed wind speeds;
- Small differences in the sensitivity of each of the turbines to wind speed or small differences of the observed wind speed by each of the turbines;
- The influence of one turbine to the other, where a turbine can lower the impact speed on the next turbine due to its proximity.

An overview of the details of all identified storm events between September 2015 and December 2016 is given in Appendix 1. In those overviews, several statistical indicators are determined:

- The total power loss, in % and in MW;
- The maximal power variation measured during the entire storm event within 15 minutes, 30 minutes and 60 minutes, also in % and in MW;
- The cut out (table 4) or cut in (table 5) duration;
- The storm duration.

Out of these tables 2 important conclusions can be drawn:

1. A high volatility in storm event duration is observed. It goes from 2 to 12 hours;
2. The cut-in phase goes in a majority of cases faster than the cut-out phase. This could be explained by similar operational criterias applied in storm situation to determine when a wind turbine can start to produce again (example: when the wind speed is measured for a certain duration below the cut out wind speed limit).

## SEASONALITY OF STORM EVENTS

The 16 observed storms in the studied period (September 2015 to December 2016) show a strong seasonality. All storms occurred between September and March. Even though this cannot be a definitive conclusion because only 16 months of data were analysed, the available wind speed measurements for the period 2000 to 2017 shows that this observation can be generalized.

The figure 7 below represents for the 16 years of measurement (**axis X)** the number of time a wind speed measurement (average measure with 15 min basis **in axis Y)** is registered beyond the storm threshold wind speed; including the margin calculated in section 2.2.

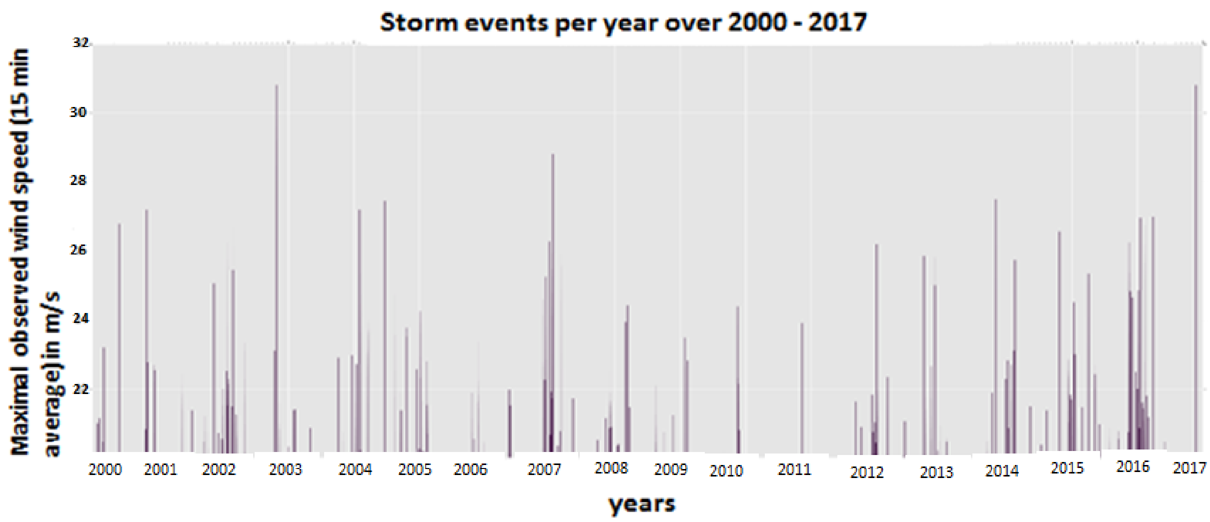


*Figure 7 - Plot of the wind speed for January 2000 to January 2017 for the moments the wind speed exceeds the threshold value of 20 m/s.*

#### MAJOR STORM EVENTS

As stated above in this study, only one major event has been observed in the period between September 2015 and January 2017 for which offshore turbines with 30 m/s cut out wind speed also suffered a cut-out. Looking at the historical wind speed measurements available at the moment of this study, it can be concluded that this **kind of event is rare** and should not happen every year (on the contrary of the other kind of storms (moderate and small).

> Disclaimer
>
> The period studied and the data available at the moment of this study are not detailed enough to assess with precision the frequency of occurrence of major storm events. Furthermore, external factors having an influence on this frequency rate such as global warming have not been considered here.

## 3.3. Statistical analysis of ramping events

To obtain the results presented in this section, 3E used the following data:

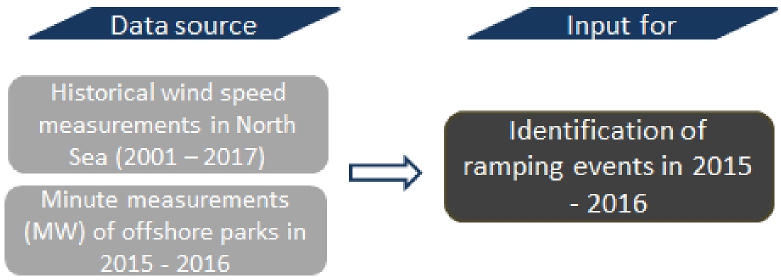


*Figure 8 – data used for the analysis of ramping events*

#### USED METHODOLOGY

In the section on definitions a ramping event was defined as follows**:** ‘rapid power variation (loss or gain) observed in a certain period of time. This power variation is caused by a wind speed fluctuation’.

Two parameters influence the identification of a ramping event: the timeframe studied and the size of power variation measured. For this analysis, ELIA defined 4 different size of power variation: 150 MW; 300 MW, 450 MW and 600 MW combined to 4 different durations: 7.5 minutes, 15 minutes, 30 minutes and 60 minutes.

Given the 1 minute time resolution of the available data and the use of a moving timeframe in the analysis, an entire year of statistics consists of 526 600 possible occurrences.

#### RAMPING STATISTICS

The results calculated for 2016 are summarized in the table 6 below. For example: a power variation of 150 MW (measured on the offshore production in 2016, which corresponds to an installed capacity of 712 MW) observed in a time interval of 7.5 minutes happened 0.03 % of the time (27 occurrences).

| 2016 | 150 MW | | 300 MW | | 450 MW | | 600 MW | |
|---|---|---|---|---|---|---|---|---|
| | Loss | Gain | Loss | Gain | Loss | Gain | Loss | Gain |
| 7.5 min | 0,03% (27) | 0,02% (19) | 0,003% (1) | 0,003% (1) | 0 | 0 | 0 | 0 |
| 15 min | 0,2% (52) | 0,1% (58) | 0,008% (2) | 0,009% (3) | 0 | 0 | 0 | 0 |
| 30 min | 0,7% (113) | 0,6% (131) | 0,05% (21) | 0,06% (20) | 0,003% (3) | 0,002% (1) | 0 | 0 |
| 60 min | 1,8% (178) | 2,0% (199) | 0,2% (35) | 0,2% (41) | 0,02% (8) | 0,02% (8) | 0,004% (1) | 0 |

*Table 4 – Overview of ramping event occurrence in 2016*

Out of the results presented in the table above, it can be concluded that the frequency of occurrence of ramps significant enough to influence ELIA's system imbalance (or ELIA's reserves) is very limited. A power variation of 150 MW (which correspond approximatively to ELIA's aFRR volume contracted) in 15 minutes only happens 0.2 % of the time).

## Seasonality and symmetry

To determine whether the ramping event were also dependent on the season, 3E analysed also their repartition over the entire year. The graph below represents the observed maximal ramps (in both upward and downward directions) in a time window of 15 minutes on the entire year (axis x represents the days of the year).

It can be concluded that, on the opposite to storm events, the season of the year does not influence the occurrence of ramping events. Furthermore, it is observed that the occurrence of ramping events is symmetrical on a daily basis. This means that on the days on which a high upward ramp is observed, generally also a downward ramp of similar magnitude occurs.

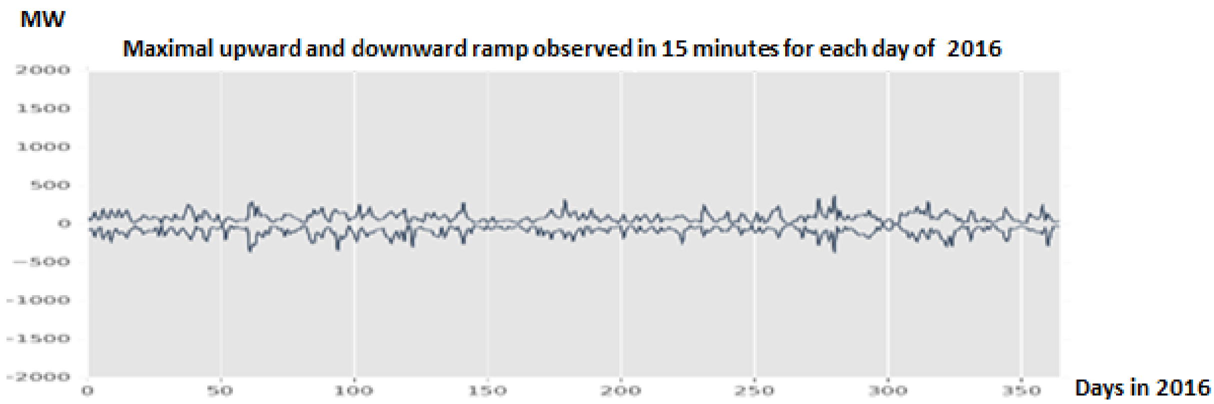


Figure 9 - Maximum observed upward and downward ramp in a time window of 15 minutes per day of the year in 2016

# 4. Statistical assessment of future storm and ramping events

To calculate the results of this section, 3E used the following data:

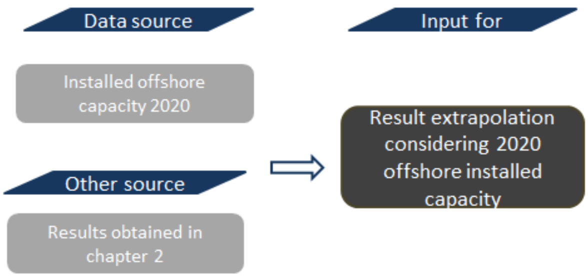


*Figure 10 – data used for the extrapolation to 2020*

## 4.1. Extrapolation production data to 2020

As stated in previous section, one-minute time series data of the offshore production at park level has been provided for the period September 2015 – December 2016. On top of this data, ELIA also gave the expected installed capacities in years 2018, 2019 and 2020. In order to assess the occurrences and risks of storms and ramps beyond 2020 an extrapolation is done by combining both data sets.

To elaborate the power production profiles of the future offshore parks, 3E started with the analysis of the power production profile of the 3 parks (Northwind, Belwind and C-Power) in production at the moment of the study.

3E calculated the Pearson coefficients for each wind park (statistical measures of linear correlation between 2 variables. i.e. value of 1 means a total positive correlation). As illustrated by the figure below, power production profiles are highly correlated (Pearson coefficients range from 0.937 to 0.999, with an average of 0.953). Given that:

- Even the Pearson correlation coefficients between the parks located farthest from each other are high;
- The turbines of Belwind and Northwind have different cut out wind speed limits than the turbines in C-Power, which lowers their correlation with C-Power, and;
- The currently existing parks almost take-up the maximum geographic range of the designated zone for offshore wind.

**3E** assumes that a production profile of the added installed capacity between 2017 and 2020 can be generated with sufficient accuracy as a capacity-weighted mean of the different production profiles of the existing parks. The resulting production profile has an average Pearson coefficient of 0,98 with the existing offshore parks.

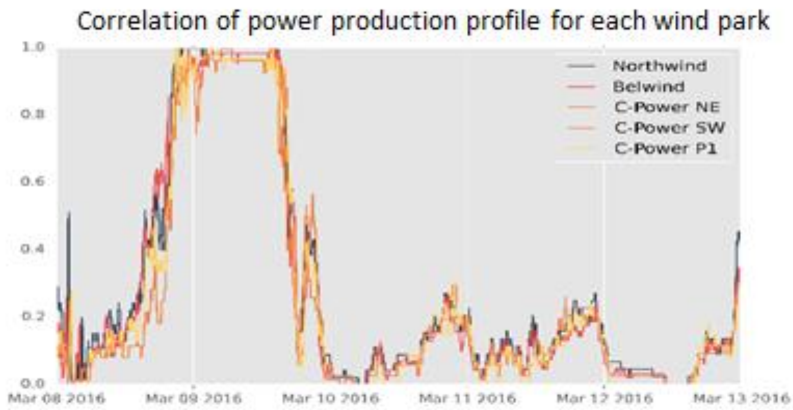


Figure 11- Example normalized time series of (left) the production of the current offshore wind parks indicating a high correlation between the different parks

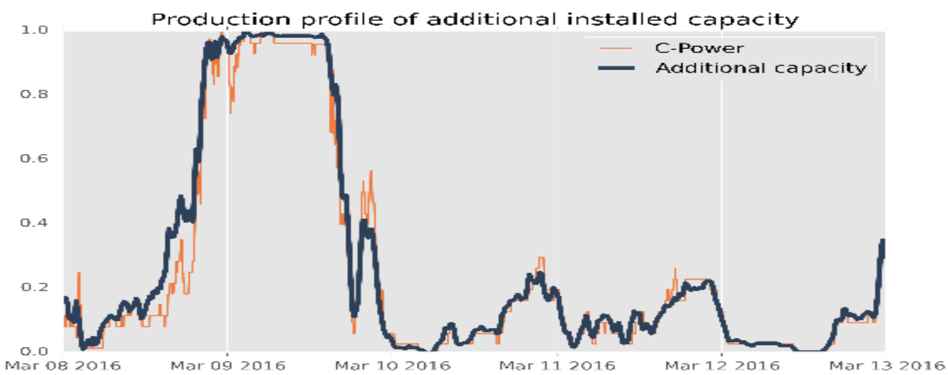


*Figure 12- comparison of the production profile of the additional installed capacity between 2017 and 2020 with an example park*

## 4.2. Scenarios on technical capabilities of future wind parks

As illustrated by the results of chapter 2 of this study, the cut out wind speed limit of the relevant wind turbines is an important factor that influences the magnitude and frequency of storm events: a park with a cut out wind speed limit of 25 m/s will be impacted by a moderate storm at least 4 times per year (number of moderate storms observed in 2015 and in 2016) whereas a new park with a cut out wind speed limit of 30 m/s would only be impacted by a major storm less than once a year.

Moreover, this cut out wind speed technology evolves continuously. As a consequence, alternatives to the current two cut out wind speed scenarios described in this study exist. New technologies offered by different wind turbine manufacturers are avoiding an immediate and instantaneous cut out once the technical limit is reached and proposes a decreasing production once wind speed overrun 25 m/s. An example is the "High Wind Ride Through" technology proposed by Siemens[5] and described hereunder:

5 https://www.siemens.com/content/dam/internet/siemens-com/global/market-specific-solutions/wind/brochures/infographic-high-wind-ride-through.pdf

The left graph below represents an immediate cut out (at wind turbine level) once the technical threshold is reached (25 m/s or 30 m/s for example). The right graph illustrates one alternative to the immediate cut out with a smoother power decrease once the technical threshold is reached.

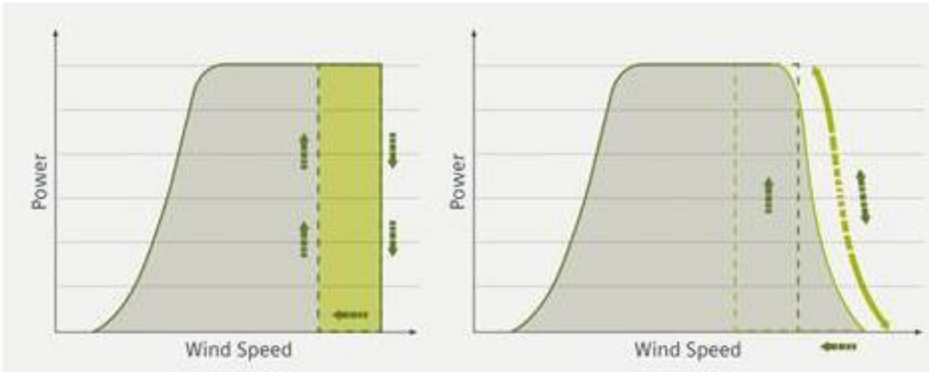


*Figure 13 – example of positive evolution in wind speed cut out technology*

In order to make a robust assessment of future events of storm risk different scenarios have been developed considering different potential technical configurations:

Scenario A
Worst case
immediate cut out

| Installed capacity | Cut out wind speed |
|---|---|
| **1966** MW | 25 m/s |
| 326 MW | 30 m/s |

Scenario B
Intermediate case
Linear cut out

| Installed capacity | Cut out wind speed |
|---|---|
| 1287 MW | 25 m/s |
| 679 MW | 25 - 32 m/s |
| 326 MW | 30 m/s |

Scenario C
Intermediate case
Linear cut out

| Installed capacity | Cut out wind speed |
|---|---|
| 552 MW | 25 m/s |
| 1414 MW | 25- 32 m/s |
| 326 MW | 30 m/s |

Scenario D
Best case
Immediate cut out

| Installed capacity | Cut out wind speed |
|---|---|
| 552 MW | 25 m/s |
| 1740 MW | 30 m/s |

*Figure 14 – scenarios for the extrapolation to 2020*

Disclaimer

Additional scenarios could be thought of based on other technologies than the one used in these simulations and applicable to the cut out wind speed limit. However, the objective of this study is not to realize a detailed market assessment to investigate all possible related technologies but to propose a limited number of realistic scenarios that cover a majority of possibilities for 2020 offshore configuration. Moreover, the final technical choice made by the wind park producers has no influence on ELIA's proposed solutions formulated in chapter 6 of this document.

## 4.3. Extrapolation of storm events to 2020

For the scenarios A, B & C, the table built in chapter 2 are extended to 2020 for both cut out and cut in phases. These tables are presented in Appendix A of this document.

The figure below details how the linear cut out wind speed limit is implemented in the model for the extrapolation of 2020 in scenarios B & C.

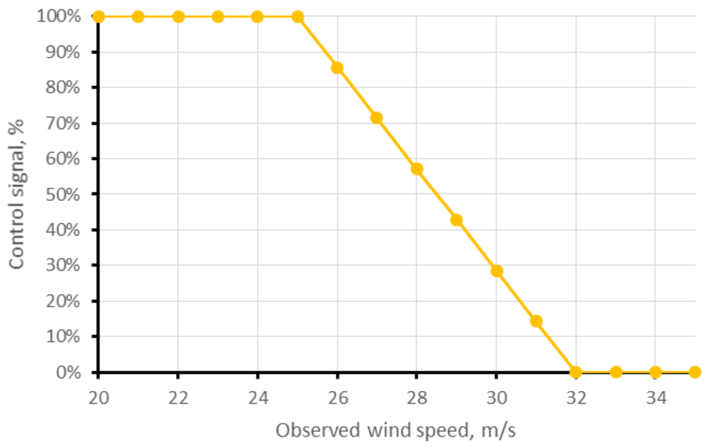


*Figure 15 – linear cut out wind speed parameter used for extrapolation in scenarios B & C.*

The detailed results of the analysis of future storm events can be found in appendix B[6]. The table 5 below summarizes key results (in terms of power loss observed on the entire storm event) for the four scenarios investigated. Taking the assumption that some (or all) market parties will follow the technological evolution observed on the wind turbine cut out limit, it is observed in scenarios B and C that a moderate storm event can cause a power loss above 1000 MW and whatever the scenario, an major storm would cause an impact beyond 2000 MW.

| storm category | Power loss (MW)- scenario A | | | Power loss (MW) - scenario B | | | Power loss (MW) - scenario C | | | Power loss (MW) - scenario D | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | min | max | average | min | max | average | min | max | average | min | max | average |
| small | 622 | 1062 | 812 | 413 | 965 | 576 | 237 | 522 | 372 | 176 | 308 | 241 |
| moderate | 1548 | 1806 | 1393 | 1048 | 1638 | 1333 | 449 | 1476 | 960 | 463 | 547 | 505 |
| major | 2144 | | | 2143 | | | 2136 | | | 2131 | | |

*Table 5: power loss per storm category and scenarios for 2020*

In addition to the results summarized in the table 8 above, it is observed that the maximal power variation in 15 minutes can reach 700 MW for the cut out phase and more than 850 MW for the cut in phase. Fluctuation of this order of magnitude might significantly influence ELIA's control area in both directions in case Balancing Responsible Parties are not capable in handling these production variations.

[6] In the tables presented in Appendix A of this study, some extrapolated results are highlighted in red. The reason comes from the available wind speed data (single source of measurement) used as input for this study which is not taken at the exact same localisation and altitude of the wind turbine. Even though these measurements have been verified and corrected by 3E, slight errors can still occur as a consequence of the extrapolation. These errors are identified in red (counter intuitive values)

## 4.4. Extrapolation of Ramping events in 2020

In this section the same logic as for the extrapolation of storm events is used: the results obtained in chapter 3 for the ramping events are used to generate the results considering the expected 2020 installed offshore capacity. The results presented in the table below clearly illustrate an increase of frequency of occurrence of ramping events. In this way, a power variation of 150 MW in 15 minute of time will happen 17 times more in 2020 than the observations made for 2016.

The impact of this increase in ramping event occurrence on the imbalance of the Belgian Control Area will need to be resolved by the activation of automatic frequency restoration reserves (aFRR or R2).

> The exact impact on ELIA's secondary reserve needs to be investigated in a broader perspective than just in the context of offshore wind production as there are other parameters triggering its activation. This is not in the scope of this study

Table 6 below presents the results for all 4 size of ramping event investigated as well as for the different time horizon defined.

| 2020 | 150 MW | | 300 MW | | 450 MW | | 600 MW | |
|---|---|---|---|---|---|---|---|---|
| | Loss | Gain | Loss | Gain | Loss | Gain | Loss | Gain |
| 7.5 min | 1,37% (231) | 1,52% (240) | 0,22% (86) | 0,23% (105) | 0,053% (39) | 0,055% (43) | 0,016% (15) | 0,015% (15) |
| 15 min | 3,57% (284) | 3,87% (297) | 0,79% (163) | 0,6% (131) | 0,25% (76) | 0,22% (81) | 0,089% (40) | 0,084% (38) |
| 30 min | 8,01% (319) | 8,05% (318) | 2,12% (228) | 2,34% (233) | 0,78% (128) | 0,81% (147) | 0,36% (78) | 0,33% (83) |
| 60 min | 13,66% (335) | 13,48% (332) | 5,00% (272) | 5,25% (279) | 2,04% (193) | 2,27% (211) | 0,96% (120) | 1,01% (139) |

*Table 6 – overview of ramping event occurrence in 2020. % represent the fraction of time (during the year) these ramping event are observed while the number of days (over the year) is given between parenthesis.*

# 5. Forecastability of storm and ramping events

In this section, 3E verifies which data source (among those made available by ELIA and summarized in chapter 2 of this study) is the most adequate (i.o.w gives the best results) to predict storm and ramping events. To do so, 3E and ELIA used the following data as illustrated by figure 15 below:

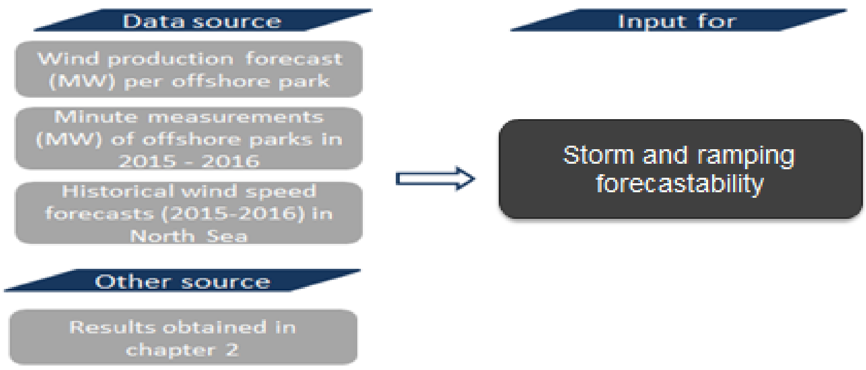


*Figure 16 – overview of data used for forecastability of storm and ramping events*

## 5.1. Forecastability of storm events

The extrapolation results obtained in the previous section for each scenario showed potentially important power fluctuation in both directions (cut out and cut in phases) in reaction to a storm event. Those power fluctuations will happen in short time intervals and could cause significant perturbation on the Belgian balancing Area.

However, it can be assumed that individual production variations are not completely transposed to the imbalance of the Belgian Balancing Area as – just like any generation asset – an offshore park needs to be included in a portfolio of a Balancing Responsible Party. This one will have the responsibility to keep its portfolio balanced, even in case of storm events.

The BRP ability to balance its portfolio in case of storm events – and therefore the pro-active actions taken by BRPs - will depend on the accuracy and reliability of the weather forecast model used for storm detection.

3E investigated – from wind forecasts and weather data made available by ELIA at the moment of this study – different storm prediction methodologies to identify which data source is the most adapted input to a storm prediction model.

### ELIA'S WIND PRODUCTION FORECASTS

This methodology uses the results obtained in the statistical assessment (chapter 3) to determine the average characteristics of a storm event. In this way, 3E and ELIA calculated that an average storm event corresponds to a power loss of 350 MW with a cut out duration of 3 hours.

In a second phase 3E verified in ELIA's day ahead and intraday wind production forecasts how often these characteristics (i.e: 350 MW power variation in a timeframe of 3 hours) were forecasted.

An advantage of this method is that it allows the detection of "**false positive**" events, being a power variation presenting the characteristics of an average storm identified in day ahead or intraday forecasts but that did not occurred in reality (i.o.w : not reflected by in the analysis of minute power measurements of offshore parks).

On the contrary, the disadvantage of this method is that it cannot make the difference between a "storm event" and a ramping event. In this way, the total number of events identified with this method (for a power variation of 350 MW and a timeframe of 3h) is equal to 286.

The results obtained are summarized in the table below. 3E performed sensitivities on the exact start of the power variation and on the characteristics of an average storm event.

| Ratio of successfully forecasted events | | | | | | |
|---|---|---|---|---|---|---|
| power loss within time interval | *Sensitivities on the exact start of the storm event* | | | | | |
| | | ±0h | ±1h | ±2h | ±3h | ±4h |
| 350 MW, 3h | Day-ahead | 1,0% | 4,9% | 14,0% | 23,1% | 31,8% |
| | Intraday | 4,3% | 10,5% | 20,3% | 32,5% | 42,3% |
| 300 MW, 4h | Day-ahead | 2,6% | 10,9% | 26,5% | 37,6% | 45,1% |
| | Intraday | 6,2% | 20,7% | 34,4% | 42,7% | 51,1% |

*Table 7 - fraction of the successfully forecasted events in which determined power losses occurs in a specific timeframe*

The forecast rates obtained with this methodology are not satisfying enough. The limited potential of ELIA's wind speed forecasts to detect major events such as storms can be explained by the current parametrization of ELIA's wind power forecast data used for the simulation: the production value (MW) forecasted for each park corresponds to the 50$^{th}$ percentile[7] (P50) while major events are per definition rare and require specific parametrization (often beyond the 90$^{th}$ percentile (P90)).

### WIND SPEED FORECASTS

The third methodology starts from the wind speed forecasts[8] available on the period studied and modelled from wind speed measurements taken in the North Sea nearby (even though not on the exact wind park localisation nor the same altitude) the offshore wind parks. These forecasts cover a period of 4 days (granularity of 3 hours) and are updated every 3 hours. Before being published, each forecast is analysed and corrected (if needed) by a meteorologist.

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[7] A percentile is a measure used in statistics indicating the value below which a given percentage of observations in a group of observations fall. For example, the 50th percentile is the value below which 50% of the observations may be found.

[8] http://www.kustweerbericht.be

Applying this methodology, a storm is considered forecasted once the wind speed forecast (average 10 minutes) goes beyond the cut out wind speed threshold of the parks.

This last methodology has 3 advantages:

1) It allows the identification of “false positive events” being average wind speed forecasted beyond technical cut out limit of the wind turbine but not confirmed in the analysis of minute wind production measurements;

2) It excludes “ramping events” and specifically focuses on storm events as it considers wind speed data combined with wind turbine technical cut out limit (disadvantage of the second method investigated and described above);

3) Forecast quality improvement once it gets closer to real time can be evaluated as wind speed forecasts cover a time horizon of 96 hours.

Out of this analysis, it can be concluded that:

1) All moderate and major storm events (9 in total) were predicted in intraday forecasts ;

2) Only 3 “false positive” events when considering intraday forecasts (identified storms not confirmed in the minute production measurements)

3) 5 out of these 9 events were predicted with a time horizon longer than intraday (between D-3 to D-1);

4) 15 “false positive events” were predicted when considering forecasts with a time horizon longer than intraday (from D-3 to D-1).

### CONCLUSIONS ON STORM EVENT FORECASTABILITY

Considering the results obtained with these 2 methodologies, it can be concluded **that wind speed forecasts are the most relevant input** to use for storm prediction. A storm prediction model based on this input **can deliver reliable results in intraday**. Furthermore, some events may even be detected at a longer time horizon (until D-3).

As ELIA does not dispose yet of a forecast model based on wind speed data, **it is recommended to implement one**. It could be possible to get even more accurate results (in both intraday and day ahead) if ELIA could access to measurement data (historical for the calibration of the prediction model and in real time) at the geographical localisation of each wind park and for an altitude corresponding to the height of the wind turbines.

Finally, it can be expected than BRPs responsible for offshore wind production, because of their access to most accurate measurement data at the exact localisation of the turbine, dispose of accurate storm forecast models allowing them to fulfil their balancing responsibility by taking mitigation measures whenever deemed necessary to cover the identified impact of a storm event on their balancing position.

## 5.2. Ramping forecastability

The forecastability of ramp events can be assessed applying the second method used for storm forecast, being a comparison between the observed power variations in a certain timeframe and the expected power variations in the intraday or day ahead wind forecasts provided by ELIA.

The table below summarizes the results obtained by 3E. The power variation and timeframe used as input for the analysis are the same than those used for the statistical assessment (see chapter 3).

| 2016 | 150 MW | | 300 MW | | 450 MW | | 600 MW | |
|---|---|---|---|---|---|---|---|---|
| | Day-ahead | Intraday | Day-ahead | Intraday | Day-ahead | Intraday | Day-ahead | Intraday |
| 7.5 min | - | - | - | - | - | - | - | - |
| 15 min | 16-17% | 8-17% | 33-66% | 0-33% | - | - | - | - |
| 30 min | 7-11% | 8% | 5-10% | 0-10% | 0% | 0% | - | - |
| 60 min | 7-11% | 14-15% | 3-7% | 3-7% | 12% | 0% | 0% | - |

*Table 8 – Percentage of ramp days accurately forecasted*

#### Conclusions on ramping event forecastability

Out of the table 8 presented above it can easily be concluded that the use of wind production forecasts is not suited to the forecasting of ramping events. This conclusion can be extended to all data source made available by ELIA in the context of this study.

If ELIA wants to better forecast a ramping event, a specific analysis to better understand its causes is needed before being able to identify possible meteorological data that could be used as input to a ramping forecast model.

# 6. Benchmark with 5 other European countries

3E realized a benchmark with 5 other European countries to determine whether the **balancing risk** identified by ELIA was also detected by the TSO of these countries and when relevant to learn from solutions which have already been implemented and applied (if any) by these TSOs.

The 5 selected European countries and their TSOs contacted are: England (National Grid); Germany (50 Hz), Netherlands (TenneT), Denmark (Energinet) and Sweden (Svenska kraftnät).

TenneT, 50Hertz as well as National Grid and SVK reported that the topic of storms and ramping of offshore (or onshore) wind parks are of little to no importance for them as their influence on their balancing area is currently negligible. In consequence, no specific measures exist (in their current operational procedures or in their regulation).

These answers can be explained by:

1) The large geographical spread between their offshore parks: even if a storm occurs, it will only take down one (or a limited number of) park at a time and this (these) park(s) will have time to come back to full production (cut in phase observed at the end of a storm event) before the storm impacts the next park(s).

   Such chain reaction is not observed in Belgium. Because of the limited distance between parks, all of them react simultaneously to the same storm event.

2) The relatively low ratio of installed wind capacity compared to their load.

The last country (Denmark) has developed specific measurements applicable to wind production with the objective to solve a more structural issue (not a balancing risk as for Belgium), with period where the wind production could exceed peak demand. These measures are described in the section below.

## 6.1. Energinet

In comparison to the above stated TSOs, the Danish TSO Energinet faces significant challenges to integrate 1 270 MW of offshore and 3 800 MW of onshore wind in a region with a peak demand of only 6 100 MW.

The main difference with Belgian offshore configuration lays in the geographical repartition of Danish offshore parks. As illustrated by the example below, they are spread all around the country which makes the **potential balancing risk caused by a storm event less significant than for Belgium**.


*Figure 17 – example of geographical repartition of Danish offshore wind farms*

On the contrary, seen the ratio of installed wind capacity compared to Denmark peak demand, Energinet faces more **structural problems** as total wind production could overtake the Danish demand (not yet the case for Belgium). To cope with these difficulties specific measures regarding ramp and storm control are described in the Danish technical regulation (especially in its section 5.3.2) and summarized hereunder in the following 3 sections:

### CONSTRAINT FUNCTIONS

The Danish technical regulation states that all wind power plants must be equipped with constraint functions, *i.e.* supplementary active power control functions, to avoid instability or overloading of the public electricity supply grid in connection with switching in the public electricity supply grid. Three distinct constraints are defined:

1) An absolute power constraint used to limit active power from a wind power plant to a set point-defined maximum power limit in the Point of Connection. This is mainly used to protect the public electricity supply grid against overload in critical situations.

2) A delta power constraint used to constrain the active power from a wind power plant to a required constant value in proportion to the possible active power. This is typically used to establish a regulating reserve for regulation purposes in connection with frequency control.

3) A ramp rate constraint used to limit the maximum speed by which the active power can be changed in the event of changes in wind speed or active power set points. It is this constraint that is normally used for reasons of system operation to prevent the changes in active power from adversely impacting the stability of the public electricity supply grid. Control using a new parameter for the active power ramp rate constraint must be commenced within two seconds and completed no later than 10 seconds after receipt of an order to change the parameter. The maximum standard value for the ramp rate constraint is 100 kW/s.

### SYSTEM PROTECTION

All Danish wind power plants must be equipped with system protection – a control function which must be capable of very quickly regulating the active power supplied by a wind power plant to one or more predefined set points based on a downward regulation order. Set points are determined by the electricity supply undertaking upon commissioning within the framework laid down by the transmission system operator.

The wind power plant must have at least five different configurable regulation step options. The following regulation steps are recommended as default values: Up to 70%, 50%, 40%, 25% and 0% of the rated power.

When performing downward regulation, the shut-down of individual wind turbines is allowed. Regulation must be commenced within one second and completed no later than 10 seconds after receipt of a downward regulation order.

Finally, if upward regulation is ordered for the system protection, e.g. from step 4 (25%) to 3 (40%), an increased order completion time is acceptable if caused by the design limitations of the plant's wind turbines or other plant components.

### Active power control

A wind power plant of category C and D (i.e. plants above 1.5 MW) must be able to reduce active power generated in the event of high wind speeds, before the wind turbines' built-in protective function is activated (at the cut-out wind speed).

This is because the stability of the public electricity supply grid must be maintained during major weather conditions, including high wind speeds. As a minimum, the wind power plant must be equipped with an automatic downward regulation function that makes it possible to avoid a transitory interruption of the active power production at wind speeds exceeding the cut-out wind speed of the wind turbines.

It must be possible to activate/deactivate the control function using orders.

Downward regulation can be performed as continuous or discrete regulation. Discrete regulation must have a step size of maximum 25% of rated power within the hatched area shown in Figure 16. When performing downward regulation, the shutdown of individual wind turbines is allowed.

The downward regulation band must be agreed with the transmission system operator upon commissioning of the wind power plant. The width of the downward regulation band may depend on local wind conditions.

All of the requirements of Danish regulation described above also exist in Belgian regulation (a.o: in the Federal Grid Code and in the connection contracts). In addition to these, ELIA will investigate if additional constraints (e.g: ramp up limitation) need to be implemented to cover the balancing risks raised by this study (e.g: power variation around 1000 MW within 15 minute of a cut in phase).

This need for new requirements will be analyzed during the elaboration of new operational processes identified by ELIA in chapter 7

## 6.2. Conclusions of Benchmark

The elements gathered on these 5 European countries confirm the unique configuration of Belgian offshore wind parks, which are located so close to each other than a common behaviour in storm situations is observed by ELIA. As a consequence, the potential impact on ELIA’s balancing area will only differ by the technical cut out wind speed limit of each wind turbine and its order of magnitude will depend on the Balancing Responsible Parties ability to forecast the event and implement preventive mitigation measures to keep its portfolio balanced at all times.

Because of this unique configuration, ELIA must develop new specific tools and operational processes and cannot start from lessons learned of other TSOs. The mitigation measures set up by ELIA are detailed in the following chapter.

# 7. Recommendations and conclusions

## 7.1. With regards to storm events

### Tools

The results obtained in the second chapter of this study show that a significant impact can be expected as consequence to a storm event once the offshore installed capacity increases to 2300 MW. For the majority of events and independent of the final technical decisions of offshore producers on cut out wind speed criteria, **this impact will overtake 1000 MW (**as illustrated by results of Scenarios A, B and C).

In the fourth chapter, ELIA and 3E demonstrated that – under the condition to have access to the relevant measurement data – a weather model forecast could be used to detect the occurrence of storm. This detection may happen in day ahead and will be confirmed **in intraday** with high accuracy rate.

Seen the potential impact of power loss caused by a storm in 2020, ELIA must **develop a specific storm forecast model**. To do so, **new data sources that will be used for model calibration must be made available to ELIA**, with for example but not exclusively wind speed measurement for each wind park.

Furthermore, because not all storm events can be forecasted, ELIA should **also improve its real time monitoring** on offshore production with the ambition to detect as soon as possible the start of a storm event that was not expected. In order to do so, ELIA will **need accurate real time information** (e.g: real time signal indicating the number of turbine currently producing…). The exhaustive list of information needed by ELIA will be confirmed and detailed in the relevant contracts.

### Operational procedures

To dispose of an accurate forecasting tool is a pre-requisite to the **elaboration of new operational procedures specifically dedicated to cope with a detected storm event.**

In this way, ELIA will implement 3 new operational procedures that will require the collaboration of the offshore balancing responsible parties. Their objectives are to reinforce and better coordinate the actions taken by BRPs (and if needed as back up by ELIA in (or close to) real time) in answer to the detected event. By doing so, the imbalance caused by the storm will be limited at its maximum while the BRPs respect their balancing responsibilities.

#### *Once the storm event is forecasted*

The first process focuses on preventive actions and mitigation measures foreseen by the BRP once the storm risk is confirmed by the weather forecasts. As this event is predicted and can be anticipated, the elaboration and application of preventive measures falls within offshore BRP's responsibilities. During this phase, the BRPs offshore will at least confirm to ELIA:

- The storm risk (for example if additional weather forecast models are used on their side);

- Which mitigation measures he foresees to cover the identified risk. The BRP has here the flexibility to elaborate the measures that are most optimal for him, taking into consideration its own portfolio characteristics

- The timing applicable to these mitigation measures.

## *In real time or close to real time*

This second process details the actions ELIA may take in addition to those applied by the BRPs or as fall back solution if the impact caused by the storm on the imbalance is not limited as expected or if the risk is too high (in case of major storm events for example, where the impact on the imbalance could be as high as 2 GW). Here, the distinction is made between small, moderate and major storms.

A. Small and moderate storms

ELIA will monitor its imbalance at all times. If, in real time ELIA notices the need to reduce the storm impact on its control area and therefore limit in time and volume the use of its reserve activated to cover the imbalance caused, ELIA may decide to use its **exhausted reserve process**.

The **exhausted reserve process** is a new operational rule that is an obligation coming from European regulation (System Operation Guidelines). It will be detailed in the LFC Bloc agreement, a methodology that will be published by ELIA in 2018 for public consultation before being submitted to the regulator. Therefore, its description is not in the scope of this study. For clarity, an example can however already be given with the description of how to use and activate slow start units in this context that will be part of the exhausted reserve process.

B. Major storms

These storms are rare events that can potentially cause an immense impact (more than 2 GW) considering 2020 installed offshore capacity. To cover such risk, ELIA will foresee a specific process in which ELIA may apply before the event occurrence its exhausted reserve process in parallel with decremental bids on offshore parks. By doing so, ELIA aims at reducing the storm impact to volumes covered by its reserves.

The financial mechanism applicable in case of use of the exhausted reserve process is not in the scope of this study but will be described in a later stage, once the operational procedures related to this process are described, consulted and approved by regulator via the LFC Bloc agreement.

The aim of the financial mechanism should be to ensure that the BRPs responsible for the offshore wind parks are in line with the overall BRP responsibility/philosophy which is to always be incentivized to manage the balance of its offshore park by himself and not to rely on ELIA's reserve to do so.

*Once the storm is over and offshore production can start again*

In the third and the fourth chapter of this document, the possible power variation in both directions (cut out and cut in) for very short durations (15 minutes, 30 minutes and 60 minutes) were calculated. Applied to 2020 offshore installed capacity, it gave volumes of power variation that would significantly impact ELIA's perimeter (e.g : a positive power variation (from 0 production to full production) of almost 900 MW within 15 minutes).

To avoid such non-coordinated power variations, ELIA will implement with the offshore balancing responsible parties a specific operational process whose objective will be to analyse whether the proposed timing and ramps are within the operational safety limits.

Concretely, as soon as a storm event is detected the BRP[9] responsible will take contact with ELIA to coordinate the estimated timing of come back to its initial production level. Knowing that BRP's portfolio must remain balanced, the following information's will at least be communicated (on top of its mitigation measures):

- The timing he suggests to follow (upon ELIA's approval) to start producing again;
- The ramps he intends to apply (upon ELIA's approval) during this "cut in" phase;

The ramps suggested by the BRP must always comply (lower or equal to) with the technical limits calculated by ELIA.

## 7.2. With regards to ramping events

The results obtained in the analysis of ramping event showed on one hand their reduced influence on ELIA's control area in 2016 due to the relatively low installed offshore capacity and on the other hand the limited impact it would cause considering 2020 offshore configuration (with 3 % of the time where a ramping event of 150 MW within 15 minutes would be observed).

In parallel, 3E highlighted the need for an additional analysis to be performed by ELIA to determine if other data sources / meteorological parameters could be used to better forecast the most important ramp events.

[9] The operational and contractual implementation including determination of roles and responsibilities are subject to further analysis

# APPENDIX A: Statistical analysis of storm events on 2015 - 2016

| | Total power loss | | Max. 15 min ramp | | Max. 30 min ramp | | Max. 60 min ramp | | Cut-out duration | Storm duration |
|---|---|---|---|---|---|---|---|---|---|---|
| | % | $MW_{2016}$ | % | $MW_{2016}$ | % | $MW_{2016}$ | % | $MW_{2016}$ | | |
| Small storms | | | | | | | | | | |
| 14.09.15 | 45% | 173,7 | 28% | 108,1 | 38% | 146,7 | 45% | 173,7 | 0h 42m | 1h 23m |
| 15.09.15 | 35% | 135,1 | 35% | 135,1 | 35% | 135,1 | 35% | 135,1 | 0h 21m | 4h 18m |
| 18.11.15 | 52% | 200,7 | 16% | 61,7 | 20% | 77,2 | 24% | 92,6 | 4h 33m | 6h 46m |
| 21.11.15 | 43% | 165,9 | 36% | 138,9 | 43% | 165,9 | 43% | 165,9 | 0h 20m | 1h 30m |
| 26.01.16 | 54% | 208,4 | 21% | 81,1 | 36% | 138,9 | 47% | 181,4 | 1h 30m | 7h 29m |
| 29.01.16 | 34% | 131,2 | 13% | 50,2 | 16% | 61,7 | 20% | 77,2 | 6h 16m | 6h 41m |
| 01.02.16 | 36% | 138,9 | 11% | 42,5 | 14% | 54 | 19% | 73,3 | 3h 08m | 4h 57m |
| Moderate storms | | | | | | | | | | |
| 17.11.15 | 98% | 378,3 | 22% | 84,9 | 36% | 138,9 | 51% | 196,8 | 4h 39m | 11h 52m |
| 29.11.15 | 86% | 331,9 | 40% | 154,4 | 67% | 258,6 | 86% | 331,9 | 1h 01m | 2h 05m |
| 30.11.15 | 94% | 362,8 | 41% | 158,3 | 54% | 208,4 | 57% | 220 | 2h 14m | 6h 59m |
| 21.12.15 | 83% | 320,4 | 31% | 119,7 | 54% | 208,4 | 74% | 285,6 | 1h 29m | 3h 41m |
| 07.01.16 | 96% | 370,6 | 58% | 223,8 | 90% | 347,4 | 96% | 370,5 | 0h 34m | 2h 48m |
| 14.01.16 | 97% | 374,4 | 22% | 84,9 | 35% | 135,1 | 53% | 204,5 | 2h 54m | 12h 53m |
| 07.02.16 | 96% | 370,6 | 40% | 154,4 | 40% | 154,4 | 56% | 216,1 | 3h 14m | 4h 10m |
| 28.03.16 | 89% | 343,5 | 24% | 92,6 | 37% | 231,6 | 55% | 169,8 | 1h 52m | 7h 43m |
| Extreme storms | | | | | | | | | | |
| 20.11.16 | 94% | 656 | 67% | 479 | 91% | 647 | 91% | 649 | 1h 36m | 5h 13m |

*Overview of key statistical indicators on identified* ***cut-out*** *(storm) events between September 2015 and December 2016 categorized as described above*

| | Total power loss | | Max. 15 min ramp | | Max. 30 min ramp | | Max. 60 min ramp | | Cut in duration | Storm duration |
|---|---|---|---|---|---|---|---|---|---|---|
| | % | $MW_{2016}$ | % | $MW_{2016}$ | % | $MW_{2016}$ | % | $MW_{2016}$ | | |
| Small storms | | | | | | | | | | |
| 14.09.15 | 44% | 169,8 | 34% | 131,2 | 44% | 169,8 | 44% | 169,8 | 0h 30m | 1h 23m |
| 15.09.15 | 3% | 11,5 | 1% | 3,8 | 2% | 7,7 | 2% | 7,7 | 1h 28m | 4h 18m |
| 18.11.15 | 56% | 216,1 | 26% | 100,3 | 39% | 150,5 | 53% | 204,5 | 1h 30m | 6h 46m |
| 21.11.15 | 42% | 162,1 | 32% | 123,5 | 39% | 150,5 | 42% | 162,1 | 0h 37m | 1h 30m |
| 26.01.16 | 48% | 185,2 | 13% | 50,1 | 20% | 77,2 | 33% | 127,3 | 2h 44m | 7h 29m |
| 29.01.16 | 35% | 135,1 | 31% | 119,6 | 35% | 135,1 | 35% | 135,1 | 0h 25m | 6h 41m |
| 01.02.16 | 32% | 123,5 | 21% | 81 | 25% | 96,5 | 25% | 96,5 | 1h 40m | 4h 57m |
| Moderate storms | | | | | | | | | | |
| 17.11.15 | 99% | 382,1 | 34% | 131,2 | 50% | 193 | 75% | 289,5 | 2h 20m | 11h 52m |
| 29.11.15 | 85% | 328,1 | 40% | 154,4 | 71% | 274 | 85% | 328,1 | 0h 52m | 2h 05m |
| 30.11.15 | 88% | 339,6 | 22% | 84,9 | 34% | 131,2 | 55% | 212,3 | 2h 58m | 6h 59m |
| 21.12.15 | 84% | 324,2 | 27% | 104,2 | 46% | 177,5 | 58% | 223,8 | 2h 12m | 3h 41m |
| 07.01.16 | 94% | 362,8 | 60% | 231,6 | 92% | 355,1 | 94% | 362,8 | 0h 54m | 2h 48m |
| 14.01.16 | 96% | 370,5 | 37% | 142,8 | 52% | 200,7 | 69% | 266,3 | 3h 16m | 12h 53m |
| 07.02.16 | 96% | 370,5 | 72% | 277,9 | 94% | 362,8 | 96% | 370,5 | 0h 36m | 4h 10m |
| 28.03.16 | 98% | 378,2 | 44% | 169,8 | 61% | 235,4 | 98% | 378,2 | 0h 59m | 7h 43m |
| Extreme storms | | | | | | | | | | |
| 20.11.16 | 94% | 656 | 32% | 229 | 51% | 362 | 79% | 566 | 2h27 | 5h 13m |

*Table 9 - Overview of all identified* ***cut-in*** *(storm) events between September 2015 and December 2016, categorized as described above.*

# Appendix B: detailed overview of extrapolation to 2020 for scenarios A, B & C.

In the tables presented in Appendix B of this study, some extrapolated results are highlighted in red. The reason comes from the available wind speed data (single source of measurement) used as input for this study which is not taken at the exact same localisation and altitude of the wind turbine. Even though these measurements have been verified and corrected by 3E, slight errors can still occur as a consequence of the extrapolation. They are identified in red (counter intuitive values)

| | Total power loss | | | Max. 15 min ramp | | | Max. 30 min ramp | | | Max. 60 min ramp | | | Cut-out duration | Storm duration |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | % | MW 2016 | MW 2020 | % | MW 2016 | MW 2020 | % | MW 2016 | MW 2020 | % | MW 2016 | MW 2020 | | |
| Partial cut-out events of the parks with a 25 m/s threshold | | | | | | | | | | | | | | |
| 14.09.15 | 45% | 173,7 | 876,1 | 28% | 108,1 | 530,9 | 38% | 146,7 | 726,8 | 45% | 173,7 | 802,9 | 0h 42m | 1h 23m |
| 15.09.15 | 35% | 135,1 | 297,7 | 35% | 135,1 | 235,7 | 35% | 135,1 | 297,7 | 35% | 135,1 | 297,7 | 0h 21m | 4h 18m |
| 18.11.15 | 52% | 200,7 | 1062,3 | 16% | 61,7 | 293,9 | 20% | 77,2 | 360,5 | 24% | 92,6 | 435 | 4h 33m | 6h 46m |
| 21.11.15 | 43% | 165,9 | 810,7 | 36% | 138,9 | 635,6 | 43% | 165,9 | 810,7 | 43% | 165,9 | 810,7 | 0h 20m | 1h 30m |
| 26.01.16 | 54% | 208,4 | 959,2 | 21% | 81,1 | 382,7 | 36% | 138,9 | 636,8 | 47% | 181,4 | 829,4 | 1h 30m | 7h 29m |
| 29.01.16 | 34% | 131,2 | 622,1 | 13% | 50,2 | 237 | 16% | 61,7 | 280,6 | 20% | 77,2 | 359,6 | 6h 16m | 6h 41m |
| 01.02.16 | 36% | 138,9 | 632,2 | 11% | 42,5 | 186,8 | 14% | 54 | 239,1 | 19% | 73,3 | 327,8 | 3h 08m | 4h 57m |
| Total cut-out events of the parks with a 25 m/s threshold | | | | | | | | | | | | | | |
| 17.11.15 | 98% | 378,3 | 1802,8 | 22% | 84,9 | 393,7 | 36% | 138,9 | 642,6 | 51% | 196,8 | 926,1 | 4h 39m | 11h 52m |
| 29.11.15 | 86% | 331,9 | 1602,1 | 40% | 154,4 | 754,7 | 67% | 258,6 | 1246,3 | 86% | 331,9 | 1602,1 | 1h 01m | 2h 05m |
| 30.11.15 | 94% | 362,8 | 1805,5 | 41% | 158,3 | 760,1 | 54% | 208,4 | 1027,5 | 57% | 220 | 1027,5 | 2h 14m | 6h 59m |
| 21.12.15 | 83% | 320,4 | 1548,6 | 31% | 119,7 | 568,6 | 54% | 208,4 | 999,3 | 74% | 285,6 | 1373 | 1h 29m | 3h 41m |
| 07.01.16 | 96% | 378,6 | 1804,3 | 58% | 223,8 | 1056,9 | 90% | 347,4 | 1646,4 | 96% | 370,5 | 1793,9 | 0h 34m | 2h 48m |
| 14.01.16 | 97% | 374,4 | 1787,7 | 22% | 84,9 | 400,9 | 35% | 135,1 | 627,6 | 53% | 204,5 | 950,6 | 2h 54m | 12h 53m |
| 07.02.16 | 96% | 370,6 | 1774,3 | 40% | 154,4 | 729,6 | 40% | 154,4 | 773,6 | 56% | 216,1 | 1031,9 | 3h 14m | 4h 10m |
| 28.03.16 | 89% | 343,5 | 1806,9 | 24% | 92,6 | 640,1 | 37% | 231,6 | 824,1 | 55% | 169,8 | 1089,8 | 1h 52m | 7h 43m |
| Cut-out events including the parks with a 25 m/s threshold (upper line) and C-Power (lower line), and ramps (summed) | | | | | | | | | | | | | | |
| 20.11.16 | 94% | 364 | 1852,2 | - | 479 (67%) | 1437,6 (67%) | - | 647 (91%) | 1853,3 (86%) | - | 649 (91%) | 1862,3 (86%) | 1h 36m | 5h 13m |
| | 93% | 292 | 292 | | | | | | | | | | | |

*Table 10 - Extrapolation towards 2020 installed offshore capacity in Scenario A – cut out phase*

| | Total power loss | | | Max. 15 min ramp | | | Max. 30 min ramp | | | Max. 60 min ramp | | | Cut-in duration | Storm duration |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | % | MW 2016 | MW 2020 | % | MW 2016 | MW 2020 | % | MW 2016 | MW 2020 | % | MW 2016 | MW 2020 | | |
| Partial cut-in events of the parks with a 25 m/s threshold | | | | | | | | | | | | | | |
| 14.09.15 | 44% | 169,8 | 876 | 34% | 131,2 | 619,1 | 44% | 169,8 | 786,5 | 44% | 169,8 | 786,5 | 0h 30m | 1h 23m |
| 15.09.15 | 35% | 135,1 | 728,1 | 1% | 3,8 | 397,4 | 2% | 7,7 | 694,4 | 2% | 7,7 | 694,4 | 1h 28m | 4h 18m |
| 18.11.15 | 56% | 216,1 | 1062,3 | 26% | 100,3 | 449,7 | 39% | 150,5 | 659,2 | 53% | 204,5 | 911,7 | 1h 30m | 6h 46m |
| 21.11.15 | 42% | 162,1 | 810,7 | 32% | 123,5 | 581,6 | 39% | 150,5 | 714,4 | 42% | 162,1 | 775,1 | 0h 37m | 1h 30m |
| 26.01.16 | 48% | 185,2 | 959,2 | 13% | 50,1 | 228,7 | 20% | 77,2 | 339,9 | 33% | 127,3 | 562,7 | 2h 44m | 7h 29m |
| 29.01.16 | 35% | 135,1 | 622,1 | 31% | 119,6 | 550,9 | 35% | 135,1 | 564,6 | 35% | 135,1 | 375,7 | 0h 25m | 6h 41m |
| 01.02.16 | 32% | 123,5 | 632,2 | 21% | 81 | 354,9 | 25% | 96,5 | 414,3 | 25% | 96,5 | 414,3 | 1h 40m | 4h 57m |
| Total cut-in events of the parks with a 25 m/s threshold | | | | | | | | | | | | | | |
| 17.11.15 | 99% | 382,1 | 1802,8 | 34% | 131,2 | 535,6 | 50% | 193 | 777,8 | 75% | 289,5 | 1167,5 | 2h 20m | 11h 52m |
| 29.11.15 | 85% | 328,1 | 1602,1 | 40% | 154,4 | 733,6 | 71% | 274 | 1306,5 | 85% | 328,1 | 1581,3 | 0h 52m | 2h 05m |
| 30.11.15 | 88% | 339,6 | 1805,5 | 22% | 84,9 | 392,6 | 34% | 131,2 | 588,5 | 55% | 212,3 | 982,9 | 2h 58m | 6h 59m |
| 21.12.15 | 84% | 324,2 | 1548,6 | 27% | 104,2 | 490,2 | 46% | 177,5 | 832,3 | 58% | 223,8 | 1047,4 | 2h 12m | 3h 41m |
| 07.01.16 | 94% | 362,8 | 1804,3 | 60% | 231,6 | 1005,2 | 92% | 355,1 | 1542,4 | 94% | 362,8 | 1609,5 | 0h 54m | 2h 48m |
| 14.01.16 | 96% | 370,5 | 1787,7 | 37% | 142,8 | 655,3 | 52% | 200,7 | 908,3 | 69% | 266,3 | 1219,1 | 3h 16m | 12h 53m |
| 07.02.16 | 96% | 370,5 | 1774,3 | 72% | 277,9 | 1303,9 | 94% | 362,8 | 1714,9 | 96% | 370,5 | 1751,6 | 0h 36m | 4h 10m |
| 28.03.16 | 98% | 378,2 | 1806,9 | 44% | 169,8 | 769,7 | 61% | 235,4 | 1053,1 | 98% | 378,2 | 1716,6 | 0h 59m | 7h 43m |
| Cut-in events including the parks with a 25 m/s threshold (upper line) and C-Power (lower line), and ramps (summed) | | | | | | | | | | | | | | |
| 20.11.16 | 94%<br>97% | 359<br>297 | 1852,2<br>292 | - | 229,0 (32%) | 553,9 (26%) | - | 362,0 (51%) | 839,3 (39%) | - | 566,0 (79%) | 1349,6 (65%) | 2h 27m | 5h 13m |

*Table 11 - Extrapolation towards 2020 installed offshore capacity in Scenario A – cut in phase*

| | Total power loss | | | Max. 15 min ramp | | | Max. 30 min ramp | | | Max. 60 min ramp | | | Cut-out duration | Storm duration |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | % | MW 2016 | MW 2020 | % | MW 2016 | MW 2020 | % | MW 2016 | MW 2020 | % | MW 2016 | MW 2020 | | |
| Partial cut-out events of the parks with a 25 m/s threshold | | | | | | | | | | | | | | |
| 14.09.15 | 45% | 173,7 | 682,3 | 28% | 108,1 | 437,4 | 38% | 146,7 | 530,7 | 45% | 173,7 | 589,5 | 0h 42m | 1h 23m |
| 15.09.15 | 35% | 135,1 | 476,4 | 35% | 135,1 | 154,3 | 35% | 135,1 | 194,9 | 35% | 571,5 | 194,9 | 0h 21m | 4h 18m |
| 18.11.15 | 52% | 200,7 | 695,4 | 16% | 61,7 | 176,7 | 20% | 77,2 | 309,6 | 24% | 92,6 | 309,6 | 4h 33m | 6h 46m |
| 21.11.15 | 43% | 165,9 | 530,7 | 36% | 138,9 | 416,1 | 43% | 165,9 | 485,1 | 43% | 165,9 | 530,7 | 0h 20m | 1h 30m |
| 26.01.16 | 54% | 208,4 | 682,8 | 21% | 81,1 | 266 | 36% | 138,9 | 431 | 47% | 181,4 | 543 | 1h 30m | 7h 29m |
| 29.01.16 | 34% | 131,2 | 551,6 | 13% | 50,2 | 209,5 | 16% | 61,7 | 235,4 | 20% | 77,2 | 261,6 | 6h 16m | 6h 41m |
| 01.02.16 | 36% | 138,9 | 413,8 | 11% | 42,5 | 122,3 | 14% | 54 | 156,5 | 19% | 73,3 | 214,6 | 3h 08m | 4h 57m |
| Total cut-out events of the parks with a 25 m/s threshold | | | | | | | | | | | | | | |
| 17.11.15 | 98% | 378,3 | 1497,6 | 22% | 84,9 | 440,9 | 36% | 138,9 | 604,9 | 51% | 196,8 | 738,7 | 4h 39m | 11h 52m |
| 29.11.15 | 86% | 331,9 | 1048,8 | 40% | 154,4 | 494 | 67% | 258,6 | 815,8 | 86% | 331,9 | 1048,8 | 1h 01m | 2h 05m |
| 30.11.15 | 94% | 362,8 | 1341,6 | 41% | 158,3 | 517,8 | 54% | 208,4 | 623,3 | 57% | 220 | 671 | 2h 14m | 6h 59m |
| 21.12.15 | 83% | 320,4 | 1118,3 | 31% | 119,7 | 385,5 | 54% | 208,4 | 663,9 | 74% | 285,6 | 964,9 | 1h 29m | 3h 41m |
| 07.01.16 | 96% | 370,6 | 1181,1 | 58% | 223,8 | 691,9 | 90% | 347,4 | 107,8 | 96% | 370,5 | 1174,3 | 0h 34m | 2h 48m |
| 14.01.16 | 97% | 374,4 | 1638,4 | 22% | 84,9 | 434,4 | 35% | 135,1 | 539,3 | 53% | 204,5 | 758,8 | 2h 54m | 12h 53m |
| 07.02.16 | 96% | 370,6 | 1269,9 | 40% | 154,4 | 490,7 | 40% | 154,4 | 417,9 | 56% | 216,1 | 675,5 | 3h 14m | 4h 10m |
| 28.03.16 | 89% | 343,5 | 1570,4 | 24% | 92,6 | 519,7 | 37% | 231,6 | 872,1 | 55% | 169,8 | 947,7 | 1h 52m | 7h 43m |
| Cut-out events including the parks with a 25 m/s threshold (upper line) and C-Power (lower line) , and ramps (summed) | | | | | | | | | | | | | | |
| 20.11.16 | 94%<br>93% | 364<br>292 | 1847,7<br>292 | - | 479 (67%) | 1460,8 (68%) | - | 647 (91%) | 1744,1 (81%) | - | 649 (91%) | 1858,9 (86%) | 1h 36m | 5h 13m |

*Table 12 - Extrapolation towards 2020 installed offshore capacity in Scenario B – cut out phase*

| | Total power loss | | | Max. 15 min ramp | | | Max. 30 min ramp | | | Max. 60 min ramp | | | Cut-in duration | Storm duration |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | % | MW 2016 | MW 2020 | % | MW 2016 | MW 2020 | % | MW 2016 | MW 2020 | % | MW 2016 | MW 2020 | | |
| Partial cut-in events of the parks with a 25 m/s threshold | | | | | | | | | | | | | | |
| 14.09.15 | 44% | 169,8 | 682,3 | 34% | 131,2 | 315,1 | 44% | 169,8 | 377,3 | 44% | 169,8 | 377,3 | 0h 30m | 1h 23m |
| 15.09.15 | 35% | 135,1 | 476,4 | 1% | 3,8 | 260,1 | 2% | 7,7 | 453 | 2% | 7,7 | 476,4 | 1h 28m | 4h 18m |
| 18.11.15 | 56% | 216,1 | 695,4 | 26% | 100,3 | 294,4 | 39% | 150,5 | 431,6 | 53% | 204,5 | 596,8 | 1h 30m | 6h 46m |
| 21.11.15 | 42% | 162,1 | 530,7 | 32% | 123,5 | 320,6 | 39% | 150,5 | 467,7 | 42% | 162,1 | 507,4 | 0h 37m | 1h 30m |
| 26.01.16 | 48% | 185,2 | 682,8 | 13% | 50,1 | 149,7 | 20% | 77,2 | 222,5 | 33% | 127,3 | 368,4 | 2h 44m | 7h 29m |
| 29.01.16 | 35% | 135,1 | 551,6 | 31% | 119,6 | 270,9 | 35% | 135,1 | 381,6 | 35% | 135,1 | 416,3 | 0h 25m | 6h 41m |
| 01.02.16 | 32% | 123,5 | 413,8 | 21% | 81 | 232,3 | 25% | 96,5 | 263,4 | 25% | 96,5 | 271,2 | 1h 40m | 4h 57m |
| Total cut-in events of the parks with a 25 m/s threshold | | | | | | | | | | | | | | |
| 17.11.15 | 99% | 382,1 | 1497,6 | 34% | 131,2 | 350,6 | 50% | 193 | 509,2 | 75% | 289,5 | 764,3 | 2h 20m | 11h 52m |
| 29.11.15 | 85% | 328,1 | 1048,8 | 40% | 154,4 | 480,2 | 71% | 274 | 855,3 | 85% | 328,1 | 1035,2 | 0h 52m | 2h 05m |
| 30.11.15 | 88% | 339,6 | 1341,6 | 22% | 84,9 | 256,9 | 34% | 131,2 | 392,8 | 55% | 212,3 | 643,5 | 2h 58m | 6h 59m |
| 21.12.15 | 84% | 324,2 | 1118,3 | 27% | 104,2 | 320,9 | 46% | 177,5 | 555,7 | 58% | 223,8 | 797,4 | 2h 12m | 3h 41m |
| 07.01.16 | 94% | 362,8 | 1181,1 | 60% | 231,6 | 658 | 92% | 355,1 | 1009,7 | 94% | 362,8 | 1053,6 | 0h 54m | 2h 48m |
| 14.01.16 | 96% | 370,5 | 1638,4 | 37% | 142,8 | 428,9 | 52% | 200,7 | 594,6 | 69% | 266,3 | 798,1 | 3h 16m | 12h 53m |
| 07.02.16 | 96% | 370,5 | 1269,9 | 72% | 277,9 | 853,6 | 94% | 362,8 | 1122,6 | 96% | 370,5 | 1159,3 | 0h 36m | 4h 10m |
| 28.03.16 | 98% | 378,2 | 1570,4 | 44% | 169,8 | 503,9 | 61% | 235,4 | 689,4 | 98% | 378,2 | 1123,7 | 0h 59m | 7h 43m |
| Cut-in events including the parks with a 25 m/s threshold (upper line) and C-Power (lower line), and ramps (summed) | | | | | | | | | | | | | | |
| 20.11.16 | 94%<br>97% | 359<br>297 | 1847,7<br>292 | - | 229,0<br>(32%) | 362,6<br>(17%) | - | 362,0<br>(51%) | 549,5<br>(25%) | - | 566,0<br>(79%) | 925,9<br>(43%) | 2h 27m | 5h 13m |

*Table 13 - Extrapolation towards 2020 installed offshore capacity in Scenario B – cut in phase*

| | Total power loss | | | Max. 15 min ramp | | | Max. 30 min ramp | | | Max. 60 min ramp | | | Cut-out duration | Storm duration |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | % | MW 2016 | MW 2020 | % | MW 2016 | MW 2020 | % | MW 2016 | MW 2020 | % | MW 2016 | MW 2020 | | |
| Partial cut-out events of the parks with a 25 m/s threshold | | | | | | | | | | | | | | |
| 14.09.15 | 45% | 173,7 | 522,7 | 28% | 108,1 | 326,6 | 38% | 146,7 | 326,6 | 45% | 173,7 | 417,6 | 0h 42m | 1h 23m |
| 15.09.15 | 35% | 135,1 | 273,3 | 35% | 135,1 | 224,1 | 35% | 135,1 | 252,8 | 35% | 571,5 | 252,8 | 0h 21m | 4h 18m |
| 18.11.15 | 52% | 200,7 | 463,9 | 16% | 61,7 | 249 | 20% | 77,2 | 261,2 | 24% | 92,6 | 358,9 | 4h 33m | 6h 46m |
| 21.11.15 | 43% | 165,9 | 237,3 | 36% | 138,9 | 178,4 | 43% | 165,9 | 208,1 | 43% | 165,9 | 237,3 | 0h 20m | 1h 30m |
| 26.01.16 | 54% | 208,4 | 435,2 | 21% | 81,1 | 175,9 | 36% | 138,9 | 208,2 | 47% | 181,4 | 232,9 | 1h 30m | 7h 29m |
| 29.01.16 | 34% | 131,2 | 499,4 | 13% | 50,2 | 249,2 | 16% | 61,7 | 245,8 | 20% | 77,2 | 254,6 | 6h 16m | 6h 41m |
| 01.02.16 | 36% | 138,9 | 177,5 | 11% | 42,5 | 52,4 | 14% | 54 | 67,1 | 19% | 73,3 | 92 | 3h 08m | 4h 57m |
| Total cut-out events of the parks with a 25 m/s threshold | | | | | | | | | | | | | | |
| 17.11.15 | 98% | 378,3 | 1167,1 | 22% | 84,9 | 530,9 | 36% | 138,9 | 570,7 | 51% | 196,8 | 601,4 | 4h 39m | 11h 52m |
| 29.11.15 | 86% | 331,9 | 449,8 | 40% | 154,4 | 211,9 | 67% | 258,6 | 349,9 | 86% | 331,9 | 449,8 | 1h 01m | 2h 05m |
| 30.11.15 | 94% | 362,8 | 993,8 | 41% | 158,3 | 386,8 | 54% | 208,4 | 515,2 | 57% | 220 | 643,6 | 2h 14m | 6h 59m |
| 21.12.15 | 83% | 320,4 | 664,3 | 31% | 119,7 | 263,5 | 54% | 208,4 | 432,6 | 74% | 285,6 | 523,16 | 1h 29m | 3h 41m |
| 07.01.16 | 96% | 370,6 | 506,6 | 58% | 223,8 | 296,7 | 90% | 347,4 | 462,3 | 96% | 370,5 | 503,7 | 0h 34m | 2h 48m |
| 14.01.16 | 97% | 374,4 | 1476,8 | 22% | 84,9 | 498,6 | 35% | 135,1 | 556,7 | 53% | 204,5 | 73,9 | 2h 54m | 12h 53m |
| 07.02.16 | 96% | 370,6 | 1034,4 | 40% | 154,4 | 702,3 | 40% | 154,4 | 720,9 | 56% | 216,1 | 748,4 | 3h 14m | 4h 10m |
| 28.03.16 | 89% | 343,5 | 1388,4 | 24% | 92,6 | 549,9 | 37% | 231,6 | 935,6 | 55% | 169,8 | 975,8 | 1h 52m | 7h 43m |
| Cut-out events including the parks with a 25 m/s threshold (upper line) and C-Power (lower line) , and ramps (summed) | | | | | | | | | | | | | | |
| 20.11.16 | 94%<br>93% | 364<br>292 | 1844,1<br>292 | - | 479 (67%) | 1485,9 (69%) | - | 647 (91%) | 1625,9 (75%) | - | 649 (91%) | 1855,2 (86%) | 1h 36m | 5h 13m |

*Table 14 - Extrapolation towards 2020 installed offshore capacity in Scenario C – cut out phase*

| | Total power loss | | | Max. 15 min ramp | | | Max. 30 min ramp | | | Max. 60 min ramp | | | Cut-in duration | Storm duration |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | % | MW 2016 | MW 2020 | % | MW 2016 | MW 2020 | % | MW 2016 | MW 2020 | % | MW 2016 | MW 2020 | | |
| Partial cut-in events of the parks with a 25 m/s threshold | | | | | | | | | | | | | | |
| 14.09.15 | 44% | 169,8 | 522,7 | 34% | 131,2 | 144,3 | 44% | 169,8 | 145,1 | 44% | 169,8 | 145,1 | 0h 30m | 1h 23m |
| 15.09.15 | 35% | 135,1 | 273,3 | 1% | 3,8 | 200,48 | 2% | 7,7 | 256,5 | 2% | 7,7 | 273,3 | 1h 28m | 4h 18m |
| 18.11.15 | 56% | 216,1 | 463,9 | 26% | 100,3 | 249,3 | 39% | 150,5 | 291,3 | 53% | 204,5 | 297 | 1h 30m | 6h 46m |
| 21.11.15 | 42% | 162,1 | 237,2 | 32% | 123,5 | 200,6 | 39% | 150,5 | 210,6 | 42% | 162,1 | 217,6 | 0h 37m | 1h 30m |
| 26.01.16 | 48% | 185,2 | 435,2 | 13% | 50,1 | 158 | 20% | 77,2 | 176,3 | 33% | 127,3 | 187 | 2h 44m | 7h 29m |
| 29.01.16 | 35% | 135,1 | 499,3 | 31% | 119,6 | 157,7 | 35% | 135,1 | 225 | 35% | 135,1 | 270,5 | 0h 25m | 6h 41m |
| 01.02.16 | 32% | 123,5 | 177,5 | 21% | 81 | 99,6 | 25% | 96,5 | 116,3 | 25% | 96,5 | 177,5 | 1h 40m | 4h 57m |
| Total cut-in events of the parks with a 25 m/s threshold | | | | | | | | | | | | | | |
| 17.11.15 | 99% | 382,1 | 1167,1 | 34% | 131,2 | 345,3 | 50% | 193 | 434,6 | 75% | 289,5 | 660,9 | 2h 20m | 11h 52m |
| 29.11.15 | 85% | 328,1 | 449,8 | 40% | 154,4 | 205,9 | 71% | 274 | 366,8 | 85% | 328,1 | 443,9 | 0h 52m | 2h 05m |
| 30.11.15 | 88% | 339,6 | 993,8 | 22% | 84,9 | 310,5 | 34% | 131,2 | 318,7 | 55% | 212,3 | 373,8 | 2h 58m | 6h 59m |
| 21.12.15 | 84% | 324,2 | 664,3 | 27% | 104,2 | 239,4 | 46% | 177,5 | 360,5 | 58% | 223,8 | 526,7 | 2h 12m | 3h 41m |
| 07.01.16 | 94% | 362,8 | 506,6 | 60% | 231,6 | 282,2 | 92% | 355,1 | 433,1 | 94% | 362,8 | 451,9 | 0h 54m | 2h 48m |
| 14.01.16 | 96% | 374,4 | 1476,8 | 37% | 142,8 | 369,9 | 52% | 200,7 | 421,3 | 69% | 266,3 | 528,1 | 3h 16m | 12h 53m |
| 07.02.16 | 96% | 370,5 | 1034,4 | 72% | 277,9 | 481,5 | 94% | 362,8 | 538,7 | 96% | 370,5 | 772,6 | 0h 36m | 4h 10m |
| 28.03.16 | 98% | 378,2 | 1388,4 | 44% | 169,8 | 551,45 | 61% | 235,4 | 685,5 | 98% | 378,2 | 883,6 | 0h 59m | 7h 43m |
| Cut-in events including the parks with a 25 m/s threshold (upper line) and C-Power (lower line), and ramps (summed) | | | | | | | | | | | | | | |
| 20.11.16 | 94% | 359 | 1844,1 | - | 229,0 (32%) | 425,7 (20%) | - | 362,0 (51%) | 612,4 (28%) | - | 566,0 (79%) | 775,0 (36%) | 2h 27m | 5h 13m |
| | 97% | 297 | 292 | | | | | | | | | | | |

*Table 15 - Extrapolation towards 2020 installed offshore capacity in Scenario C – cut in phase*

# Appendix C: Used Power curves of offshore wind parks

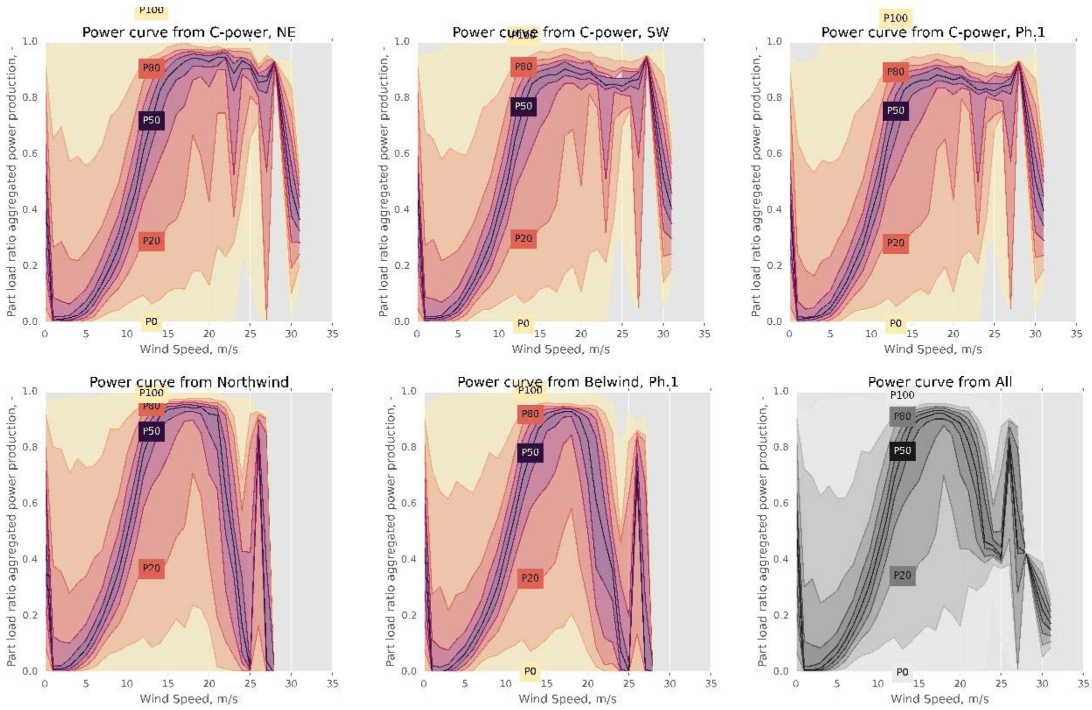


*Figure 18 - . Decile plot of the power curves of the respective offshore wind parks (coloured) and of the aggregated offshore production (grey).*

# Appendix D: List of Tables

# Appendix E: List of figures