MOG II System Integration – 2022 update

Technical report

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Preface

This study has been performed as a consultancy contract between ELIA and DTU Wind Energy following the MOG II System Integration 2022 update request by ELIA.

Roskilde, Denmark, December 2022

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Content

Summary

This document is the final report from DTU for a 2022 update on a Consultancy project on MOG II System Integration for Elia. The updated modelling results are compared to the 2020 report, available here: https://orbit.dtu.dk/en/publications/elia-mog-ii-system-integration-public-version. The 2020 study (principal study) investigated the wind power generation profiles of a 4.4 GW offshore wind power scenario (compared to a 2.3 GW installed today) in the Belgian waters, focusing on extreme wind conditions (ramps and storms) and forecast errors. This study carries out similar analyses, but for scenarios up to 5.8 GW, with updated wind technology and offshore wind power plant layout assumptions, while updating the validation of the model based on latest data on wind speeds and wind power generation.

The existing Belgian offshore fleet is one of the areas with the highest density installation of wind energy worldwide. This report studies the impact of the production variations and the forecast errors on the Elia grid when extending the Belgium offshore fleet (MOG II project). Offshore wind capacity increase of up to a total of 5.8 GW in the Belgian waters is analysed.

The validation of DTU's CorRES model to analyse the generation time series of the offshore wind power plants is updated based on wind speeds and wind power generation in Belgium until 2021. Based on the validation results, the model is considered valid for modelling the MOG II capacity extension.

For the expansion of the Belgian offshore wind fleet from the approximately 2.3 GW currently installed to the 5.8 GW scenarios, two different wind turbine specific powers are considered: a larger rotor with a lower specific power (Technology B) produces larger capacity factors but is expected to represent higher cost turbines (compared to Technology A, with higher specific power). Additionally, three storm shutdown types are modelled and compared with the "Deep" type providing least ramping during very high wind speeds. Compared to the 2020 report, larger turbines with higher hub heights are considered for the additional installations. The selected technologies are representative of the expected wind turbine technologies available for the time frame modelled, i.e., 2028-2030. As more GW are installed in the new areas compared to the 2020 report, the additional installations have a higher installation density (MW/km^2).

The focus of this study is to analyse the ramp and storm shutdown events (magnitudes and likelihoods) of the future Belgian offshore wind fleet. However, it is noteworthy to mention that compared to the 2020 report, the additional installations show higher wake losses, and consequently lower capacity factors – even as higher hub heights and larger turbines than in the 2020 report are considered. This is driven by the increased installation density. Note that the effect of climate change has not been considered as no specific information is known on the specific impact of climate change on ramps and storms[1].

Compared to the current Belgian offshore wind fleet, the standardized generation ramps are expected to be reduced towards the 5.8 GW scenarios. This is caused by larger distances between plants (i.e., geographical smoothening) and is particularly related to the locations of the new offshore wind installations being on the other side of the Belgian offshore region compared to the existing installations.

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[1] Most studies showing a significant impact of climate change on wind speeds consider time horizons towards 2050, or even 2100.

The additional 3.5 GW are installed in a separate zone, which increases the geographical spread of the installations compared to the existing 2.3 GW. Fleet-level 5 min ramps are reduced more than 1 h ramps. However, expressed in absolute power, ramps are expected to increase significantly in the future due to the larger capacity installed. In the 4.4 GW scenarios, ramps of more than 2 GW in 1 hour are expected to occur on approximately 2-6 days a year (considering both up- and down-ramps). In the 5.8 GW scenarios, this increases to 11-24 days a year, depending on the technology. Even ramps larger than 4 GW in 1 hour are seen in the 40-year simulation for the 5.8 GW scenarios, on around 1 day per year or less frequently, depending on the technology.

It is found that the largest downward ramps do not seem to occur on non-storm days (maximum wind speed lower than 20 m/s). The most extreme ramps observed during the simulated 40 years for non-storm days for the 5.8 GW scenarios are as follows:

- for 5 min ramps, down-ramps larger than 1.0 GW are expected on less than 0.1 days/year, and up-ramps larger than 1.0 GW on less than 0.1 days/year for the 25 m/s direct cut-off and not at all for the Moderate and Deep technologies;
- for 15 min ramps, down-ramps larger then 1.5 GW are expected on less than 0.5 days/year, and up-ramps larger than 1.5 GW on approximately 0.3 days/year;
- for 1 h ramps, down-ramps larger then 4.0 GW are expected on less than 0.1 days/year, and up-ramps larger than 4.5 GW on less than 0.1 days/year.

Results show that it is possible to lose the full 5.8 GW of installed capacity in all studied 5.8 GW scenarios due to an extreme storm event. The number of years where this occurs is 4-6 out of the simulated 40 years for the 5.8 GW scenarios, depending on the technology. Out of the 3 different storm protection technologies considered, the Deep shutdown type results in slower 5- and 15-min ramping during storms. For example, for 15 min ramps in the 5.8 GW scenarios on storm days, 2 GW down-ramps are expected on around 1 day per year with the 25 m/s cut-off type, but such event is not seen for the Deep type. The very large negative 1-hour ramps (larger than 3.5 GW) are reduced significantly with the Deep type compared to 25 m/s cut-off: from around 1.5 days per year to around 1 day in 10 years. Overall, the Deep type can lower all studied ramps (5 min, 15 min, 1 hour) to a level seen even on non-storm days.

The most extreme ramps observed during the simulated 40 years for storm days for the 25 m/s cut-off and Deep type in the 5.8 GW Tech B scenario (to compare the most distinct storm shutdown types in the scenario with overall largest ramps) are as follows:

- for 5 min down-ramps, larger than 2.0 GW ramps are expected on less than 0.1 days/year for the 25 m/s cut off, whereas for the Deep type larger than 1.0 GW down-ramps are not seen in the simulated data;
- for 5 min up-ramps, larger than 1.5 GW ramps are expected on less than 0.1 days/year for the 25 m/s cut-off and 2.0 GW ramps are not seen in the simulated data, whereas for the Deep type larger than 2.0 GW up-ramps are expected on less than 0.1 days/year;
- for 15 min down-ramps, larger than 3.5 GW ramps are expected on less than 0.1 days/year for the 25 m/s cut-off, whereas for the Deep type larger than 2.0 GW down-ramps are not seen in the simulated data;
- for 15 min up-ramps, larger than 4.0 GW ramps are expected on less than 0.1 days/year for both storm shutdown types;

- for 1 h down-ramps, larger than 5.5 GW ramps are expected on less than 0.1 days/year for the 25 m/s cut-off, whereas for the Deep type larger than 4.0 GW down-ramps are not seen in the simulated data;
- for 1 h up-ramps, larger than 5.5 GW ramps are expected on around 0.1 days/year for both storm shutdown types.

On storm days, extreme up-ramps are more likely than similar size down-ramps. The three analysed storm shutdown types differ in how fast the turbine shuts down during a storm, but the return from a storm happens as fast in all the types. Thus, even with the Deep type (the smoothest studied storm shutdown type), the up-ramps during the return from a storm (i.e., wind speed getting lower and turbines starting to produce again) remain significant. Mitigation of such up-ramp events after storms can be considered necessary as they represent some the largest power fluctuation events.

Geographical smoothening is also expected to decrease aggregate forecast errors (in standardized generation), as on aggregate it is easier to forecast a larger than a smaller region. However, in GW terms, the forecast errors increase towards the 5.8 GW of installations. Day-ahead forecast errors of more than 3.0 GW (negative / generation lower than forecasted or positive / generation higher than forecasted) are expected to occur a few days a year in the 5.8 GW scenarios, whereas for the latest available forecasts such errors occur on less than 1 day a year. Looking at latest available forecast errors larger than 2.5 GW in the 5.8 GW scenarios, the Deep type shows on average slightly lower errors compared to the 25 m/s cut-off. The capability of the Deep type to reduce generation forecast uncertainty (even as the quality of wind speed forecasts is the same) relates to error in wind speed having a different impact on the generation forecast error for wind speeds above 24 m/s.

In the 40-year simulation, positive day-ahead forecast errors larger than 4.5 GW are seen for all 5.8 GW scenarios (0.1 days/year), and negative day-ahead forecast errors larger than 4.5 GW are seen for half of the 5.8 GW scenarios. For the last forecasts, larger than 4.5 GW forecast errors (positive or negative) are not seen in the simulated data.

Note that the results on forecast errors do not consider any increase in the plant-level accuracy of forecasts compared to the recent past – all the changes are driven by geographical smoothening, and the increasing installed capacity. Nevertheless, forecasting can be expected to continue to improve as it did during the last decades. The actual simulated forecast and forecast error values for an individual event are stochastic and can be high or low due to randomness.

1. Introduction

This study is update on a Consultancy project on MOG II System Integration for Elia conducted in 2020 for which the results are available here: https://orbit.dtu.dk/en/publications/elia-mog-ii-system-integration-public-version. The 2020 study (principal study) investigated the wind power generation profiles of a 4.4 GW offshore wind power scenario (compared to a 2.3 GW installed today) in the Belgian waters, focusing on extreme wind conditions (ramps and storms) and forecast errors. This study carries out similar analyses, but for scenarios up to 5.8 GW, with updated wind technology and offshore wind power plant layout assumptions.

The current installed capacity of wind power plants in the Belgian offshore area is approximately 2.3 GW. A framework for an additional production zone at the frontier with France is introduced, in addition to the wind zone which already exists at the frontier with the Netherlands. This new zone will allow up to 3.5 GW of additional installed capacity. The assumption used in this study is that this additional capacity will be commissioned between 2028 and 2030. Compared to the principal study, where DTU in 2020 analysed up to 4.4 GW of offshore wind in the Belgian waters, these updated assumptions thus mean studying more offshore wind installed in the Belgian waters (up to 5.8 GW compared to 4.4 GW in the principal study) and looking further ahead (up to 2030 compared to 2028 in the principal study).

The objective of this study is to define the impact of the new wind power plants on storm events, wind power ramping events and wind power forecast errors. The consequences for the grid as well as the definition of possible necessary mitigation measures are not included in the scope of this study.

The results on forecast errors do not consider any increase in the plant-level accuracy of forecasts compared to the recent past. All the reported changes are driven by geographical smoothening, and the increasing installed capacity. Nevertheless, forecasting can be expected to continue to improve as it did during the last decades – this can be considered in post-processing of the data delivered to Elia in relation to this report.

The study is based on analysis of existing data focusing on the latest 4 years (2018-2021) and on simulations of specified scenarios for the future offshore wind power in the existing and the new zones.

The effect of climate change on wind speeds (or wind direction) has not been considered as no specific information is known on the specific impact of climate change on ramps and storms. It is expected that by 2030 the impact of climate change is limited.

The report is structured as follows:

Chapter 2 describes the selected wind turbine technologies relevant for the MOG II extension towards 2030. This includes the general technical specifications of the turbines such as specific power, rated power, rotor diameter and hub height, as well as their power curves including storm protection operation.

Chapter 3 presents the scenarios studied in terms of installed capacity and of technology for the MOG II extension. It also includes the locations of the plants currently in operation used in model validation.

Chapter 4 describes the methodology used to simulate the operation of the plants in each scenario. This includes description of CorRES, the core model for simulating the time series of wind generation of both large spatial scale and temporal length. Additionally, the methodologies for wake modelling and storm shutdown modelling are explained.

Chapter 5 documents the model validation based on the generation and wind speed measurements from the currently operating plants. Validation results are analysed for several variables, such as capacity factors, generation probability distributions, ramps, high wind speed likelihoods, and forecast error probability distributions for different forecast horizons.

Chapter 6 analyses the basic statistics of the results for all capacity/technology scenarios in terms of capacity factors, standard deviation of standardized generation and probability distributions of standardized generation.

Chapter 7 presents the statistical analysis of ramping events for several time periods (5 min, 15 min and 1 hour) in terms of standardized generation and in actual GW of power fluctuation. Additionally, this chapter compares ramp likelihoods for days without high wind speeds to dissociate ramp events due to wind variations from ramp events due to storm shutdowns. Finally, this chapter concludes and gives input for mitigation of ramps in section 7.4.

Chapter 8 introduces the methodology used for identification of storm events from the 40 years of simulated generation. Additionally, this chapter analyses the resulting statistics of frequency of occurrence of such events as a function of their severity for each installed capacity/technology scenario. This chapter gives conclusions and input for mitigation of storm-related ramp events in section 8.5.

Chapter 9 presents the statistical analysis of forecast errors in terms of standardized generation and in GW for the forecasting horizons currently used by Elia (Day-ahead, intraday, and Last). Additionally, this chapter shows how the forecast errors change for days with large ramps or storm. Section 9.5 concludes the chapter, with input to mitigation of forecast errors.

2. Analysed wind technologies

The wind technology scenarios are presented to Elia's stakeholders in the MOG 2 Task Force of 1 April 2022, incorporating stakeholders' feedback received until 22 April 2022 to reach the final scenarios.

Based on the analysis of trends from historical wind turbine data carried out in the 2020 report, information of future turbines from the manufacturers, and the Technology Catalogue from the Danish Energy Agency [1], technology scenarios for future offshore wind power plants (OWPPs) to be commissioned towards 2030 are created. The 2020 report envisioned 12 MW turbines to be available for the 2026-2028 installations. However, since then the Technology Catalogue from the Danish Energy Agency [1] has updated the expected turbine size by 2030 to be 20 MW, with 15 MW turbines expected for 2025 installations. Considering that the analyzed installation years are also 2 years further in the future (2028-2030, compared to 2026-2028 in the 2020 report), the expected turbine sizes for the additional zones are thus increased to 17 MW for installation before 2030, and 20 MW for installations in 2030. The selected turbine sizes align with feedback received from the stakeholders. It is expected that there will be a few MW range of rated power from different manufacturers, but this is not expected to have significant impact on the results.

This study does not aim to use specific manufacturer technologies for the future wind turbines, but rather makes generic assumptions and supplement with sensitivity analyses where manufacturer differences and other uncertainties are considered important for the expected results regarding ramping and behavior during storms. To consider the variation in specific power (W/m^2), similar as in 2020 report, two technology scenarios, A and B, as listed in Table 1 and Table 2, are analyzed. Table 1 shows the assumptions for installations taking place before 2030, and Table 2 for installation in 2030.

The two scenarios assume same rated power but different specific power (W/m^2). From the available information about offshore wind turbines, we have observed significant differences in specific power which will impact power curves and thereby have possible impacts on ramp rates for wind speeds below rated power; the technology scenarios A and B are designed to cover the expected range of specific powers in offshore wind installations towards 2030. It should be noted that no appreciation is made of Tech A nor Tech B being expected to be cost-optimal for the new OWPPs. Rather, the aim is to cover the potential range of specific powers, to see if a low of high specific power impacts the ramp behavior of the Belgian offshore wind fleet. If the new OWPPs utilize a specific power in between Tech A and Tech B, it should not be an issue from system integration point of view, as the expected lower and upper values are already studied. The range of specific powers is in line with the Technology Catalogue from the Danish Energy Agency [1], although in this study an even wider range is considered. The specific powers of the largest recently unveiled offshore wind turbines are within the range of Tech A and Tech B, as are the turbines analyzed in a recent study published by 3E [2].

The resulting rotor diameters in the tables are a result of the rated power and specific power choices, and they align with feedback from the stakeholders. The hub heights are increased compared to the 2020 report, as the turbines are expected to be physically larger.

Table 1. Technology scenarios for offshore wind turbines for additional installations before 2030.

Technology scenario	A	B
Rated power (MW)	17	17
Rotor diameter (m)	219	262
Hub height (m)	140	165
Specific power (W/m^2)	450	316

Table 2. Technology scenarios for offshore wind turbines for additional installations in 2030.

Technology scenario	A	B
Rated power (MW)	20	20
Rotor diameter (m)	238	284
Hub height (m)	150	175
Specific power (W/m^2)	450	316

The above assumptions lead to the power curves shown in Figure 1 for the two technology scenarios, Tech A and Tech B. On top of this, based on manufacturer brochures and literature review, three high wind technology scenarios are studied also shown in Figure 1. The storm shutdown types, and shutdown and restart limits are the same as in the 2020 report, as no new information was received to suggest that they should be changed. It was observed that the Deep type is similar to the storm shutdown technologies used in recently commissioned OWPPs in Belgium.

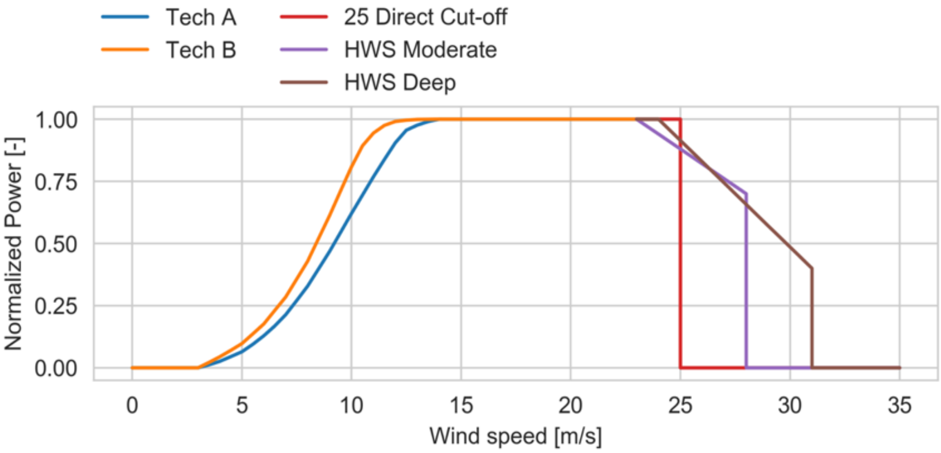

Figure 1. Power curves for assumed technology scenarios and storm shutdown types.

3. Assumptions on installed wind power capacities and scenarios

3.1 Assumptions on existing capacity considered in model validation

The plants that belong to the 0.9 GW case in Figure 2 are used in the first stage of model validation. This validation case is the same as the "BE 2018" case in the 2020 report.

During the time from writing the 2020 report to writing this report, measured data until the end of 2021 from the 2.3 GW case (the plants in 0.9 GW as well as Norther, Northwester 2, Rentel, Seastar and Mermaid) have become available. This allowed for an additional validation case to be included in this report. The 2.3 GW case also defines the existing installations in the Belgian waters; the following section describes the assumptions for the additional installations modelled on top of the existing fleet.

As in the 2020 report, the Borssele offshore cluster in the Netherlands is considered because large wake effects are expected due to its proximity to the Belgian fleet. The planed offshore plants in Dunkirk France are not modelled because their larger distance to the Belgium fleet makes them irrelevant in terms of farm-to-farm wake losses.

3.2 Assumptions on new installed capacity

This chapter starts by presenting the geographical positions of the Belgium OWPPs in the different studied scenarios based in information available when starting the simulations for this study, i.e., 22 April 2022. The first section shows the OWPPs used in model validation and the subsequent sections present the OWPP installation scenarios towards a total offshore installation capacity of 5.8 GW in the Belgian waters.

The scenarios, concerning installed capacity, i.e., 3.0 GW in 2028, 4.4 W in 2029 and 5.8 GW in 2030, are based on the latest communications of the Federal Government (https://economie.fgov.be/nl/themas/energie/energiebronnen/hernieuwbare-energieen/hernieuwbare-energiebronnen-de/belgische-offshore-windenergie), which targets an installed capacity of minimum 3.15 GW and maximum 3.5 GW in de Prinses Elisabeth-zone. To specify robust technical criteria, the study focuses on the maximum targeted capacity.

Latest available information on the location of the electric equipment are taken into account (https://economie.fgov.be/nl/themas/energie/energiebronnen/hernieuwbare-energieen/hernieuwbare-energiebronnen-de/belgische-offshore-windenergie). The order in which the new areas are utilised to reach the total of 5.8 GW (see Figure 2), was discussed and agreed with Elia.

At this point, the potential impact of gravel beds (excluding part of the offshore zone for construction for ecologic reasons) is not included: at this point there is no certainty on the exact surfaces to be excluded (and the potential impact on the offshore capacity installed and generation). While it is recognized that the impact on the capacity factor and business case of the new OWPP can be significant, the impact on the system integration simulations (forecast errors, storms, and ramps) in this study is expected to be limited. Additional simulations can still be conducted in a later phase if deemed necessary.

The several stages of the installations of the Belgium offshore wind power fleet considered in the present study are shown in Figure 2, coming in addition to the full MOG I fleet (the 2.3 GW case). The 3.0 GW scenario includes the addition of the Kavel 1 area, the 4.4 GW scenario also includes the Kavel 2 areas, and the final 5.8 GW scenarios also includes the Kavel 3 area.

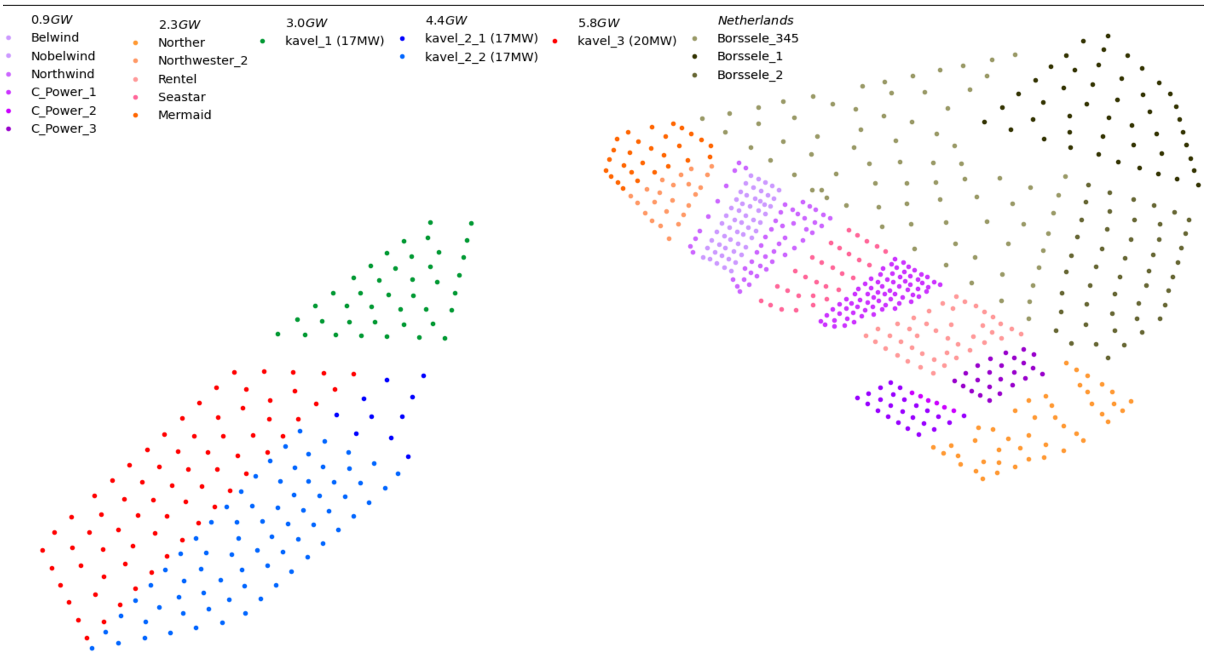

Figure 2. Plant and turbine locations for the different stages of offshore wind installations in the Belgian waters. The Dutch plants are considered when modelling external wake impacts on the Belgian OWPPs. Kavel 2 is split to two parts, based on available information.

It should be noted that the scenarios up to 4.4 GW are not identical to the 2020 report (even though the names are similar), as they do not consider the same geographical areas: e.g., the 4.4 GW scenario presented in this study uses much less space than the 4.4 GW scenario presented in the 2020 report (where the entirety of the Kavel 1-3 areas was assigned to the additional installations in the 4.4 GW scenario). Overall, the additional areas have much higher installation density (MW/km^2) compared to the 2020 report, as can be seen in Table 3.

Table 3. The additional installation areas

Name	**Installed capacity (MW)**	**Turbine capacity (MW)**	**Area (km2)**	**Installation density (MW/km^2)**
Kavel 1	700	17	46	15.2
Kavel 2	1400	17	103	13.6
Kavel 3	1400	20	107	13.1

3.3 Scenario overview

For the geographical areas described in the previous section, different turbine technologies are modelled (as presented in Chapter 1). The resulting scenarios, considering the different amounts of installations and different technologies, are listed in Table 4. All the scenarios with 3.0 GW or more installed have the same 2.3 GW as the existing installations with fixed technology; then, different amounts of additional installations with different technologies are added to the 2.3 GW to reach the total installed capacity of the scenario.

Table 4. The studied scenarios.

Name	Installed capacity (MW)	Technology	Storm shutdown type
0.9 GW	877	Known existing data	Known existing data
2.3 GW (existing)	2262	Known existing data	Known existing data
3.0 GW (year 2028)	3000: 2300 + 700 additional in Kavel 1 (with 17 MW turbines)	Tech A	25 m/s
			Moderate
			Deep
		Tech B	25 m/s
			Moderate
			Deep
4.4 GW (year 2029)	4400: as above + 1400 additional in Kavel 2 (with 17 MW turbines)	Tech A	25 m/s
			Moderate
			Deep
		Tech B	25 m/s
			Moderate
			Deep
5.8 GW (year 2030)	5800: as above + 1400 additional in Kavel 3 (with 20 MW turbines)	Tech A	25 m/s
			Moderate
			Deep
		Tech B	25 m/s
			Moderate
			Deep

For the 3.0 GW, 4.4 GW and 5.8 GW scenarios, the tech type and storm shutdown type are for the additional installed capacity; the 2300 MW part has technology specified based on known existing OWPPs. Note that the scenario 0.9 GW is called BE 2018 in the 2020 report.

4. Methodology

This chapter presents the modelling methodology applied. This includes the CorRES tool (https://corres.windenergy.dtu.dk/) for simulating the time series, and wake modelling for including wake impacts in the CorRES simulations. CorRES is an updated version of the CorWind tool used in the 2020 report.

4.1 CorRES

CorRES (https://corres.windenergy.dtu.dk/) is DTU Wind Energy's tool for simulation of wind power time series with realistic spatial and temporal correlations. It uses a database of weather time series in hourly resolution as input. All simulations are carried out using meteorological data from 1982 until 2021 included. The meteorological data in CorRES are presented in detail in [3], with the ERA5 (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5) meteorological data used in the analyses presented in this report. The meteorological data are updated compared to the 2020 report, where ERA-Interim based meteorological data were used, to the newest ERA5 reanalysis data from ECMWF (it can be noted that ERA5-based simulation showed the best performance in the comparison in [3]). The meteorological data are updated also by including 2020 and 2021 (compared to the 2020 report in which data until the end of 2019 was used).

Compared to most other available tools for large-scale wind power simulations, CorRES includes intra-hour fluctuations, which are not captured correctly by large-scale weather models, even those with high spatial and temporal resolutions. CorRES also includes turbulent fluctuations within 10 min resolutions. These fluctuations are added to the hourly weather data using stochastic simulation [4], [5].

As in the 2020 report, the CorRES simulations are carried out with a resolution of 5 min. For extreme ramp and storm cases, interpolated 1-min resolution data are provided for the time range (3 days) around each extreme case. For calibrating the plant-level storm shutdown model, specific storm cases were even simulated even on 1-s resolution.

The combination of large-scale weather data and stochastic simulation allows two types of simulations: (1) large scale regions on continental domains with several wind power plants in resolutions of up to 5 min over 40 years and (2) detailed plant simulations that model each individual turbine in resolution of up to 1 s. The latter are needed to study the impact of storm protection technologies, which are usually specified on turbine-level rather than plant-level.

Due to the limitations of CorRES, it is currently not possible to run the simulations in 1-min resolution for the full Belgium offshore fleet over the 40 years. A resolution of 5 min has therefore been selected as it provides a trade-off between the computational time and the limited added information of the within-10-min fleet power fluctuation in both simulations and in the measured data in the 1-min resolution. For each simulation, a reduced 15-min resolution dataset is also created by taking the mean of each variable in 5-min resolution (or 1-min resolution for the measured datasets) within each 15-min period.

4.2 Wake Modelling

As turbines and plants in the Belgium offshore fleet are often tightly spaced, significant wake effects are expected. DTU's PyWake software (https://topfarm.pages.windenergy.dtu.dk/PyWake/) was used to simulate wake losses. A wake is the reduction of available energy in the wind after passing each turbine. In this study the term wake loss is used to consider wakes, blockage, and added turbulence, which are all effects related to having multiple turbines near each other. A wake is the wind speed deficit. Blockage effect is when multiple turbines are in a line perpendicular to the wind, the turbines create a fictious wall, and the wind turns around to avoid it. The added turbulence means that the wind behind a turbine has increased variability.

PyWake is used to generate a plant power curve by simulating the power output of the plant as a function of the mean wind speed and mean wind direction over the whole plant. The plant power curve includes the wakes produced by other plants nearby, by modelling all the turbines within 40 km distance from each turbine within the plant. The resolution of the wake modelling has been chosen to be 1 degree in wind direction and 0.5 m/s in wind speeds. Finally, CorRES uses the plant power curve to interpolate the power produced by each plant on each time stamp.

Wake deficits are modelled using the engineering wake model proposed by Zong and Porté-Agel [6]. Moreover, the "Hybrid Induction" [7], [8] and "STF2017TurbulenceModel" [9] engineering models are used to simulate blockage and added turbulence, respectively. The modelling considers farm-to-farm wake losses. However, the so-called mesoscale losses (lack of energy recovery in the atmosphere) [10] are not considered (similar as in the 2020 report). The mesoscale losses impact very large installations, and this effect could become significant in the 5.8 GW scenario. This means that the reported CFs may be slightly overestimated. The applied wake (and blockage) modelling is similar to the related recent report on Belgian offshore wind expansion [2].

4.3 Storm shutdown behaviour

The storm shutdown modelling is carried out in the same way as in the 2020 report. When simulating multiple years of generation time series with CorRES on 5 min resolution for multiple OWPPs, the simulations need to be done on plant-level as the simulation of individual turbines is not feasible for such long time series. However, as the storm shutdown behaviours are given on turbine-level (Figure 1), the behaviours of the different shutdown technologies need to be modelled on plant-level. This section describes how the turbine-level shutdown information are transferred to plant-level models.

4.3.1 Turbine-level storm shutdown model

Individual turbine shutdown can be modelled in simulations with up to 1 s resolution in CorRES (while the weather data are hourly, CorRES creates up to 1 s time series using stochastic simulation, as described in Section 4.1). These simulations are used to study how a specific turbine high wind speed technology translates into the plant level shutdown/restart behaviour. In these simulations, each turbine in a plant is modelled. Because of the high temporal resolution and turbine-level resolution of these simulations, only specific events (one or a few days) are simulated. A selection of high wind speed events has been taken from the 40 years of weather data to represent multiple high wind cases.

In addition to the shutdown operation, the turbine-level model considers the restart operation.

An example is shown Figure 3. The continuous line is effective until the turbine is shut down due to too high wind speed (the wind speeds in the figure are 10 min averages). After the shutdown, the wind speed must get lower than the restart limit before the turbine starts to produce again. This effect is called hysteresis: it causes a time lag between the shutdown and restart operation, as it takes some time before wind speed gets lower than the restart limit after a storm event.

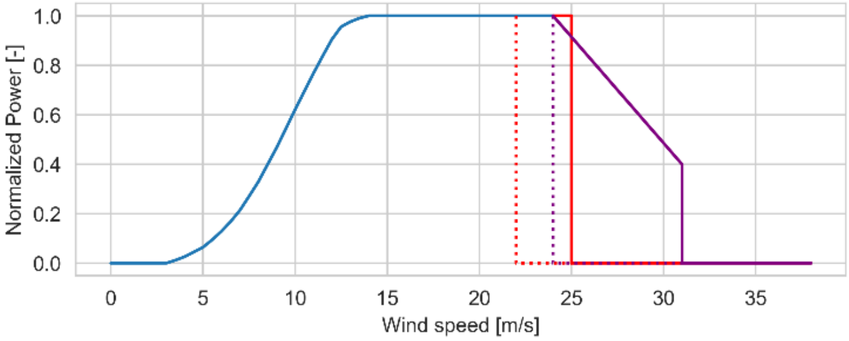

Figure 3. Storm shutdown and restart operations for the HWS Deep (magenta) and 25 m/s cut off (red) types. The dashed lines show the restart limits.

4.3.2 Resulting plant-level storm shutdown behaviours

The resulting plant-level storm shutdown behaviours for the three different shutdown types are shown in Figure 4. The blue dots show results from the 1 s resolution turbine-level runs; the red lines show the plant-level model based on the turbine-level simulations (the dashed line shows the plant-level power curve without the shutdown procedure: this line shows the power curve considering the controlled reduction of generation at high wind speeds, but without the shutdown action that takes the generation all the way to zero).

In Figure 4, the plant-level curve is smoother around the change from rated power to the part where generation is reduced compared to the turbine-level curve. Also, the cut-off does not happen as immediate on the plant-level: even for the 25 m/s direct cut-off type, the plant does not completely shut down when the plant-level 10 min wind speed gets higher than 25 m/s. This is because it is unlikely that all the turbines of the plant reach a wind speed higher than 25 m/s exactly at the same time.

Plant-level hysteresis modelling is part of the model shown in Figure 4 with red lines. This means that if wind speed decreases after reaching a wind speed value over the shutdown limit, the plant will remain partly in shutdown before the wind speed gets lower than the restart limit. This models the phenomena where some of the turbines of the plant are in shutdown, whereas others still generate.

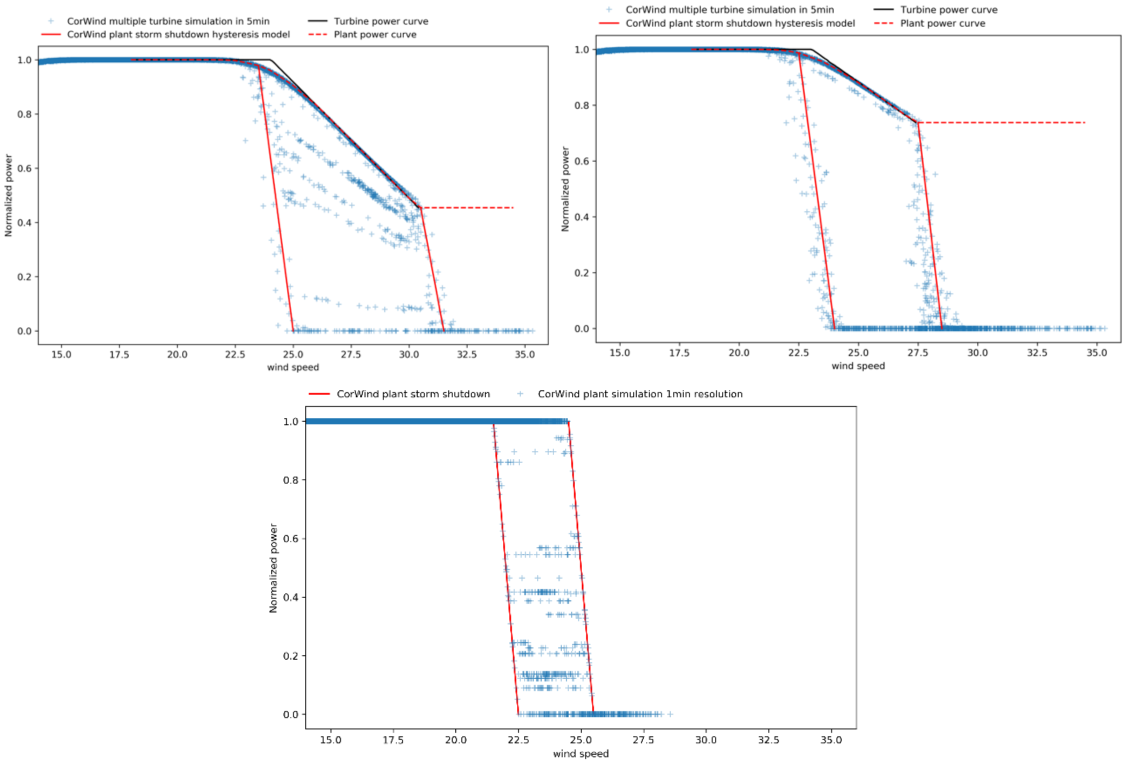

Figure 4. Calibration of storm-shutdown models in CorRES based on aggregated individual turbine simulations for different high wind speed storm operation technologies: top left: Deep; top right: Moderate; and bottom: 25 m/s direct cut-off.

4.4 Scaling of measured forecast errors for period 2018-2021

The forecast simulation part in CorRES is a based on a stochastic model, which simulates wind forecast error distributions and the spatial and temporal dependencies in the forecast errors between OWPPs. The model is similar to the one shown in [11]. The stochastic simulation model can therefore represent forecast errors statistics (see Section 5.3).

However, the simulated high and low forecast errors do not occur at the same time steps as in measured data (note that this is different compared to the modelling of actual wind generation in CorRES, which is based on weather data as described in the previous sections which ensures that the low and high actual generation occur at approximately the same time steps in measured and simulated data). This difference is a challenge if the simulated forecast error time series should be used together with measured data (e.g., measured onshore wind forecast errors), as the two datasets are not aligned in terms of when high and low forecast errors occur.

As Elia is also interested in using the simulated offshore wind forecast errors with measured data, a scaling procedure was created. The procedure allows the simulated actual offshore wind generation data from CorRES to be used with scaled measured Elia forecast data. In other words, the high and low forecast errors will then occur approximately at the same time as in the measured data. The procedure is based on observed forecast errors.

The procedure is applied only for the most recent years, 2018-2021. The scaling procedure is as follows (note that throughout the report forecast errors are defined as $e_t = p_{t,actual} - p_{t,forecast}$; all data below are fleet-level aggregates for offshore wind):

1. Take the observed forecasts for 2018-2021 ($p^{orig}_{t,forecast}$) as the starting point
2. Calculate fixed measured Elia forecast errors ($p^{fixed}_{t,foreast}$) for 2018-2021 by means of using the observed forecasts[2] ($p^{orig}_{t,forecast}$)
3. Calculate the (fixed) measured forecast errors as $e^{meas}_t = p^{meas}_{t,actual} - p^{fixed}_{t,forecast}$, where $p^{meas}_{t,actual}$ are the measured actual generation
4. Scale the measured forecast errors to represent future scenarios: $e^{scaled}_t = s_{scenario} * e^{meas}_t$
    - The scaling values $s_{scenario}$ are based on the simulated 40 years in CorRES (see column “Compared to 0.9 GW” in Table 34 for an example for Day-ahead)
    - The scaling represents the expected reduction in fleet-level forecast errors due to spatial smoothening (i.e., more spread OWPP installations)
5. Calculate the scaled forecasts as $p^{scaled}_{t,forecast} = p^{sim}_{t,actual} - e^{scaled}_t$, where $p^{sim}_{t,actual}$ are the simulated actual generation time series from CorRES (different for each scenario)
    - As e^{scaled}_t (based on measured data) and $p^{sim}_{t,actual}$ (simulated in CorRES based on weather data) are not perfectly aligned in time, $p^{scaled}_{t,forecast}$ can get infeasible values (below 0 or above installed capacity). The infeasible values were corrected to be 0 or 1 (i.e., generation at installed capacity), respectively. It was checked that these corrections do not cause any significant changes to the forecast or forecast error statistics

The resulting Day-ahead forecasts and forecast errors are visualised in Figure 5. Table 5 shows that the scaled forecast errors, i.e., e^{scaled}_t (result of step 4), show similar statistics as the Elia forecast tool in 2018-2019; in 2020-2021, the scaled forecast errors deviate somewhat from the Elia forecast tool errors, but the statistics remain similar compared to the 2018-2019 forecast errors (the deviation from the Elia forecast tool in 2020-2021 is expected[2]). The above 5 steps are done for Day-ahead, Intraday and Last forecasts.

As a final step, scaled forecast errors (steps 4 and 5) were calculated for all scenarios of interest to represent the forecasts and forecast errors statistics for the period 2018-2021 for offshore wind installed capacity up to 5.8 GW in the Belgian waters.

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[2] For 2018-Sep/2019, the results of Elia’s forecast tool are used. For Oct/2019-2021, the nominations of the wind farms are used as a proxy for the forecasts in order to mitigate the effect of an observed deviation in general forecast accuracy.

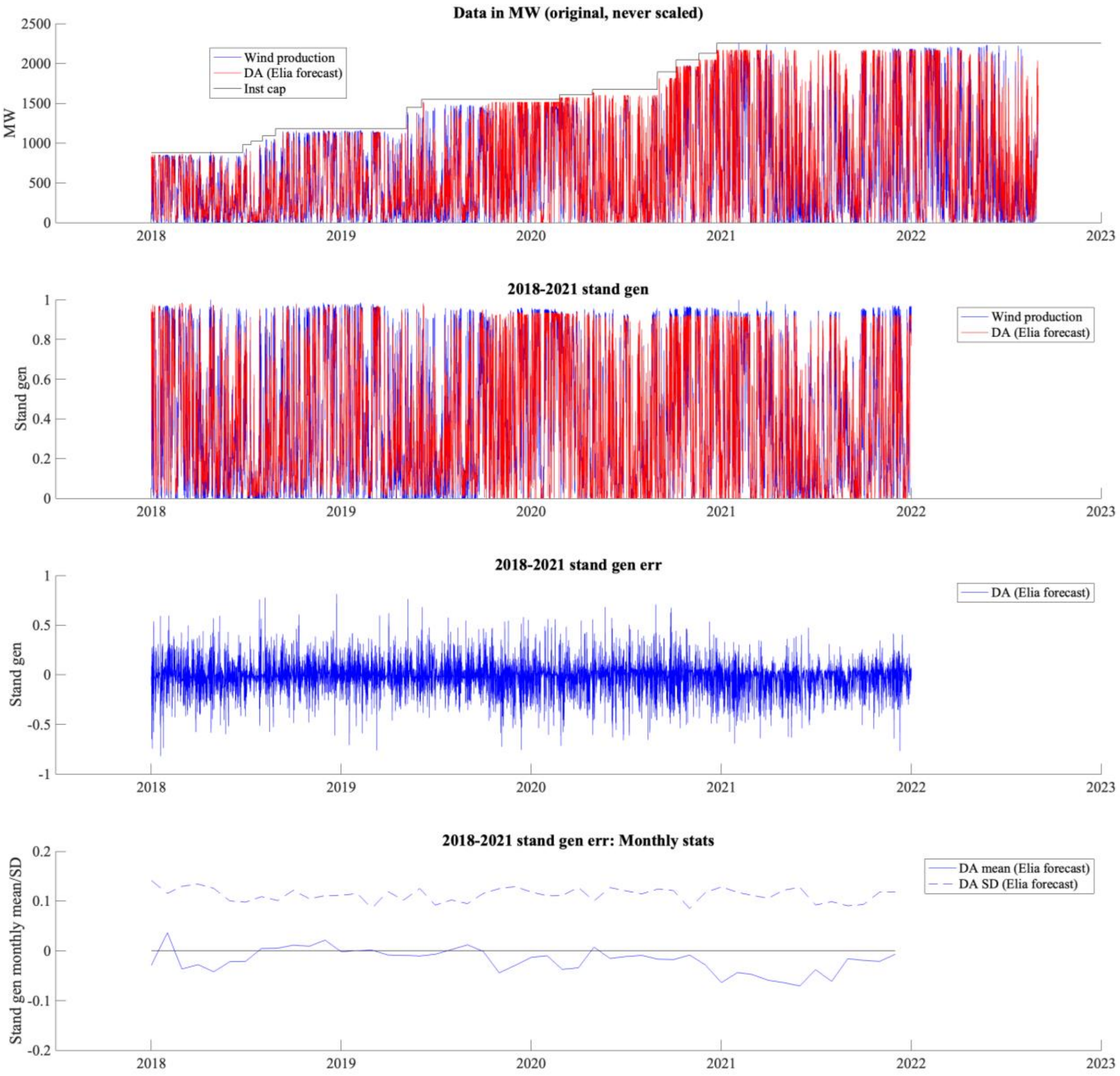

Figure 5. Visualisation of the 2018-2021 fixed measured Elia offshore day-ahead (DA) wind forecast and forecast error data (sum of the whole fleet). In the top two plots: the actual generation (blue) and the fixed Elia forecast tool data (red). In the bottom two plots: DA forecast error and its monthly mean and standard deviation (SD).

Table 5. Day-ahead forecast error statistics for the period 2018-2019.

Statistic	**Scaled forecasts**	**Elia forecast tool**
min	-0.76	-0.95
Percentile 1	-0.33	-0.36
Percentile 25	-0.06	-0.07
Percentile 50	-0.01	-0.01
Mean	-0.01	-0.01
Percentile 75	0.04	0.04
Percentile 99	0.33	0.32
max	0.84	0.81

Table 6. Day-ahead forecast error statistics for the period 2020-2021.

Statistic	Scaled forecasts	Elia forecast tool
min	-0.81	-0.96
Percentile 1	-0.38	-0.49
Percentile 25	-0.08	-0.15
Percentile 50	0.00	-0.05
Mean	-0.03	-0.08
Percentile 75	0.02	0.00
Percentile 99	0.25	0.26
max	0.74	0.80

5. Model validation

This chapter presents an update of the model validation. Compared to the 2020 report, one more year (2019) of measured data is available for the 0.9 GW case (called BE 2018 in the 2020 report). As will be described later, 2020 measured data and later are not used for the validation of the 0.9 GW case, as so much additional OWPPs are installed that the farm-to-farm wakes are not anymore comparable to the simulated 0.9 GW case. Validation of the 2.3GW case is new.

5.1 Measured data and filtering

5.1.1 Wind speed data

For the 0.9 GW case, measured wind speeds are available from the same turbines as in the 2020 report, i.e., Nobelwind, Belwind and Northwind and from C-Power. Wind speed data are available from 4 turbines per OWPP, from the 4 corners of each plant. The corner turbines are used to represent the effective average wind speed of the plant while keeping the data requirements limited. This effective average wind speed per plant is compared with the CorRES simulations, which are carried out per plant.

Wind speeds and 10 min wind speed ramps are visualized for an example OWPP in Figure 6. The ramps show a non-Gaussian shape, with significant number of large down- and up-ramps. The same behavior was seen for all measured locations. This is shown with another example, with wind speed ramps are shown in Figure 7. The distributional information on wind speeds was used in CorRES calibration (as in the 2020 report), as similar behavior was seen in measured wind speeds from all OWPPs.

For the wind speed range where wakes have an impact (approx. below 14 m/s), the measured data are expected to include wake impacts. As wind speeds from CorRES simulations are given without wake impact (with wakes considered later in the transformation from wind speed to generation), this difference is considered when comparing measured and simulated wind speeds (generation data can be compared directly between the measurements and simulations).

For the 2.3 GW case, measured wind speeds are available from the corner turbines of Norther, Rentel, Seastar, Mermaid and Northwester 2. They were handled the same way as described above for the 0.9 GW case.

Measured wind speeds were obtained in 1 min or 10 min resolution; they were averaged to 5 min or 10 min resolution, depending on the specific validation case.

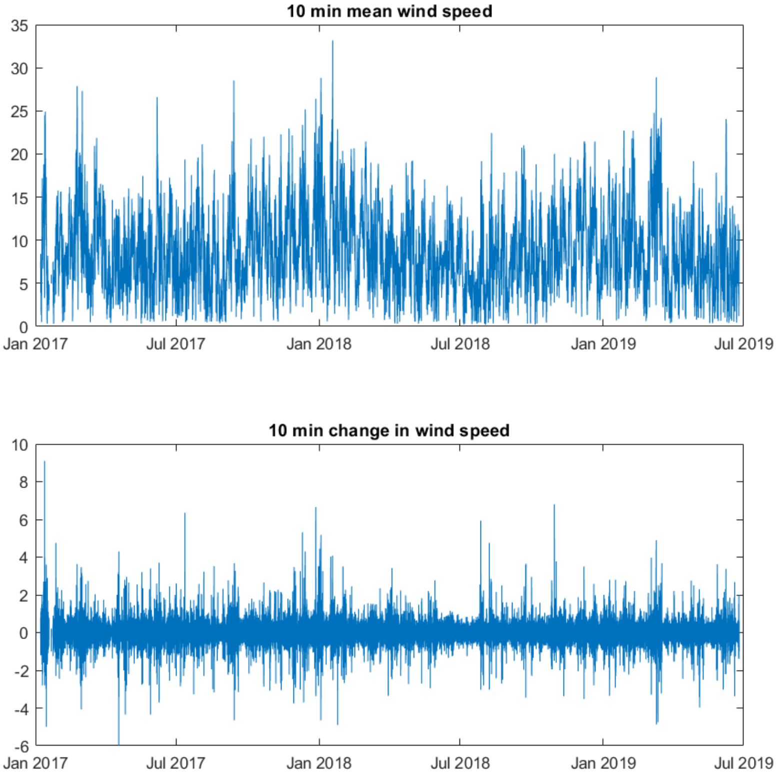

Figure 6. Measured wind speeds and 10 min wind speed ramps at an OWPP from the 0.9 GW case; 10 min resolution, mean of the 4 measured turbines.

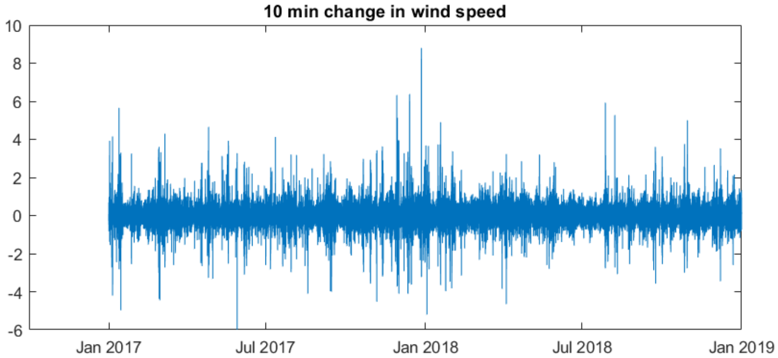

Figure 7. Measured 10 min wind speed ramps at an OWPP from the 0.9 GW case; 10 min resolution, mean of the 4 measured turbines.

5.1.2 Wind generation data and filtering

1 min resolution generation measurements for the 0.9 GW case are used with representative data for 2018 to 2019 included. These data are aggregated to 5 min resolution in model validation to assess CorRES's capability of modelling 5 min ramps, 15 min ramps and 1 h ramps. The 2019 data were not available in the 2020 report. As the wake modelling of the 0.9 GW case includes farm-to-farm wakes, measured data from the time range where approximately the same OWPPs as in the simulation case are operational, are used. Thus, 2020 and newer measured data cannot be used in the validation of the 0.9 GW case.

Note that as OWPPs are commissioned continuously, in principle new wake modelling should be calculated whenever a new OWPP is commissioned but this was not computationally feasible. Thus, the 2019 measured data are included in the validation of the 0.9 GW case, even though some additional OWPPs are commissioned in 2019. However, only generation from those OWPPs which belong to the 0.9 GW case are included in the aggregation of the measured data (so the OWPPs match the simulated case). Data after 2019 are not used, as several OWPPs belonging to the 2.3 GW case are commissioned towards 2020. Forecasts are validated in 15 min resolution, and they are available from a slightly longer time range (from July 2017 until 2019 included).

The OWPPs belonging to the 2.3 GW case are commissioned in a continuous fashion until November 2020. Similar as in the 0.9 GW case, farm-to-farm wakes are considered but no new wake model is considering whenever a single OWPP is added to the fleet. Rather, a time range where the OWPPs belonging to the 2.3 GW case are commissioned was selected (this case was defined stricter than the 0.9 GW case in terms of operational OWPPs, as the farm-to-farm wake impacts are more pronounced in the 2.3 GW case, with more OWPPs close to each other). Thus, measured data from December 2020 until the end of 2021 are used in the validation of the 2.3 GW case, and a simulation case with full wake modelling was created to model all the OWPPs belonging to the case The meteorological data in CorRES are available only until the end of 2021, so measured 2022 data are not used. Only generation from those OWPPs which belong to the 2.3 GW case are included in the aggregation of the measured data (so the OWPPs match the simulated case).

The measured generation data are in 1 min resolution, representing the measured power at Elia connection point for every individual OWPP, which were averaged to 5 min resolution for comparison to the CorRES simulations. Forecasts are validated in 15 min resolution.

It was observed in the 2.3 GW case that measured generation from several plants show very high 1 min ramps (see the time series plot in Figure 8 for an example). Many of these ramps occurred without a ramp or storm observed in the wind speed measurement but generally observed during periods with a very low imbalance price. These low imbalance prices also often occurred on times when the plant was not on the expected power curve range (see the scatter plot in Figure 8). After discussion with Elia, it was considered that these extreme 1 min ramps could be the result of downward reserve activations or voluntary output reductions (often with very fast up/down ramping) during low price periods. As the CorRES model only simulates weather driven ramps, a filter was applied to remove the non-weather driven extreme ramps. The filter was designed so that it removes (i.e., marks as NaN) measured generation data when positive imbalance price is below 0 EUR/MWh. This filtering removes approximately 10 % of the time steps.

In addition, as in the 2020 report, it is assumed that 1 min ramps of more than 10 % of the installed capacity of an OWPP when wind speed is below 18 m/s, are not weather driven (i.e., such time steps are marked as NaN). This removes an additional 0.27 % of the time steps. The full filtering result is shown Figure 9. The extreme 1 min ramps are significantly reduced, and the number of points outside of the expected power curve range (indicating unexpected generation with a given wind speed) is reduced. It was concluded that the generation time series after the filtering better reflect the weather driven ramps, and thus the filtering was applied for all OWPPs before comparing to the CorRES simulations.

In addition, the same measured data filtering of zero generation values as in the 2020 report was applied. Looking at Figure 9, there are several time steps where generation is zero even when wind speed is above 10 m/s. When comparing to simulations, the values with wind speed between 5 and 15 m/s and while measuring a generation of 0 MW are not considered (i.e., marked as NaN). This is justified as even with storm protection considered, the generation should be above 0 MW in this wind speed range. Such data points were considered to be either measurement errors or indicating that the whole OWPP is unavailable (CorRES does not model unavailability). This was done for all OWPPs.

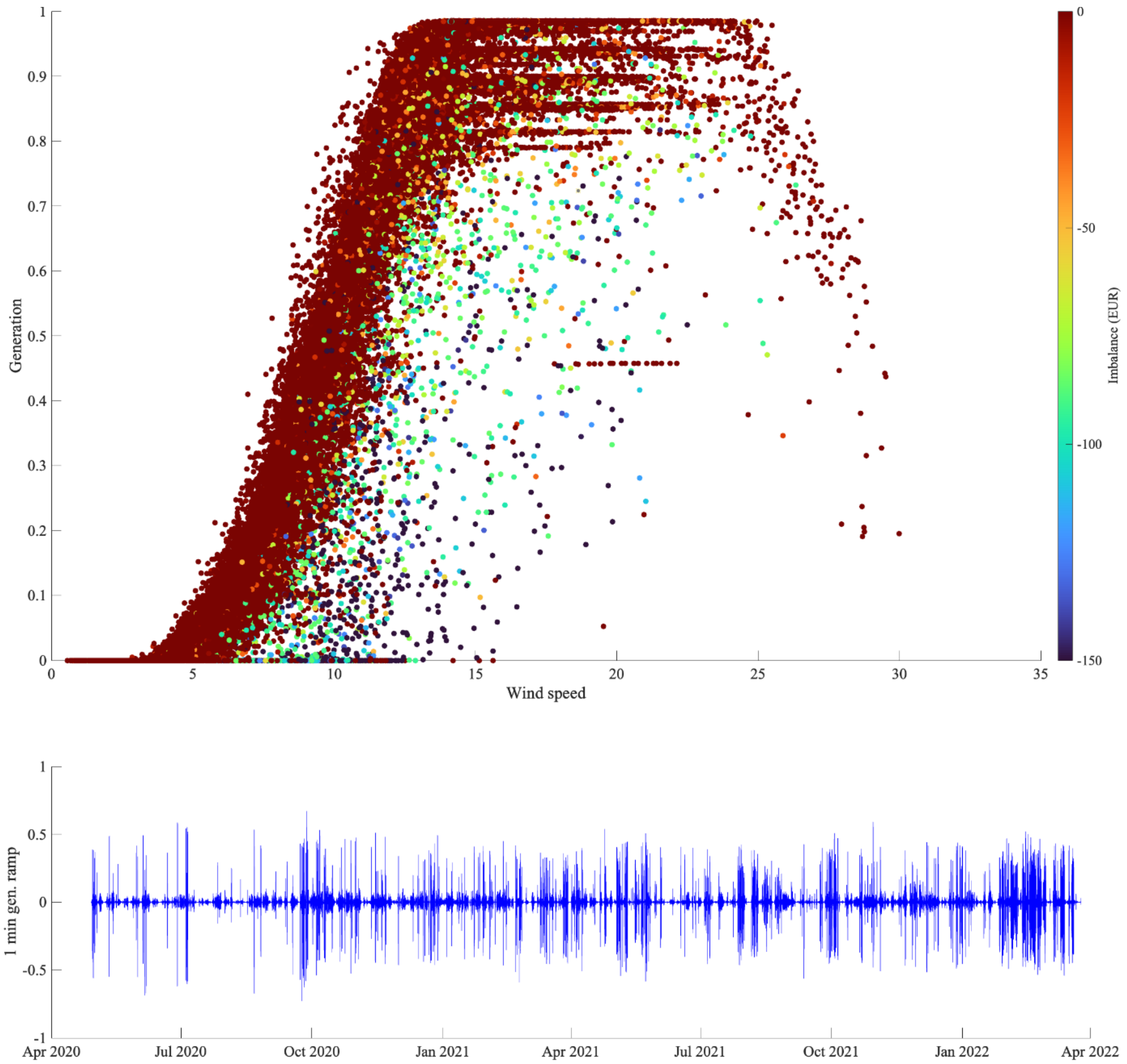

Figure 8. Measured wind speed and generation, and 1 min generation ramps without filtering for an example OWPP. Colouring is based on negative imbalance price (prices below -150 EUR are shown with the same colour as -150 EUR). All generation data are in standardised generation (1 = full installed capacity).

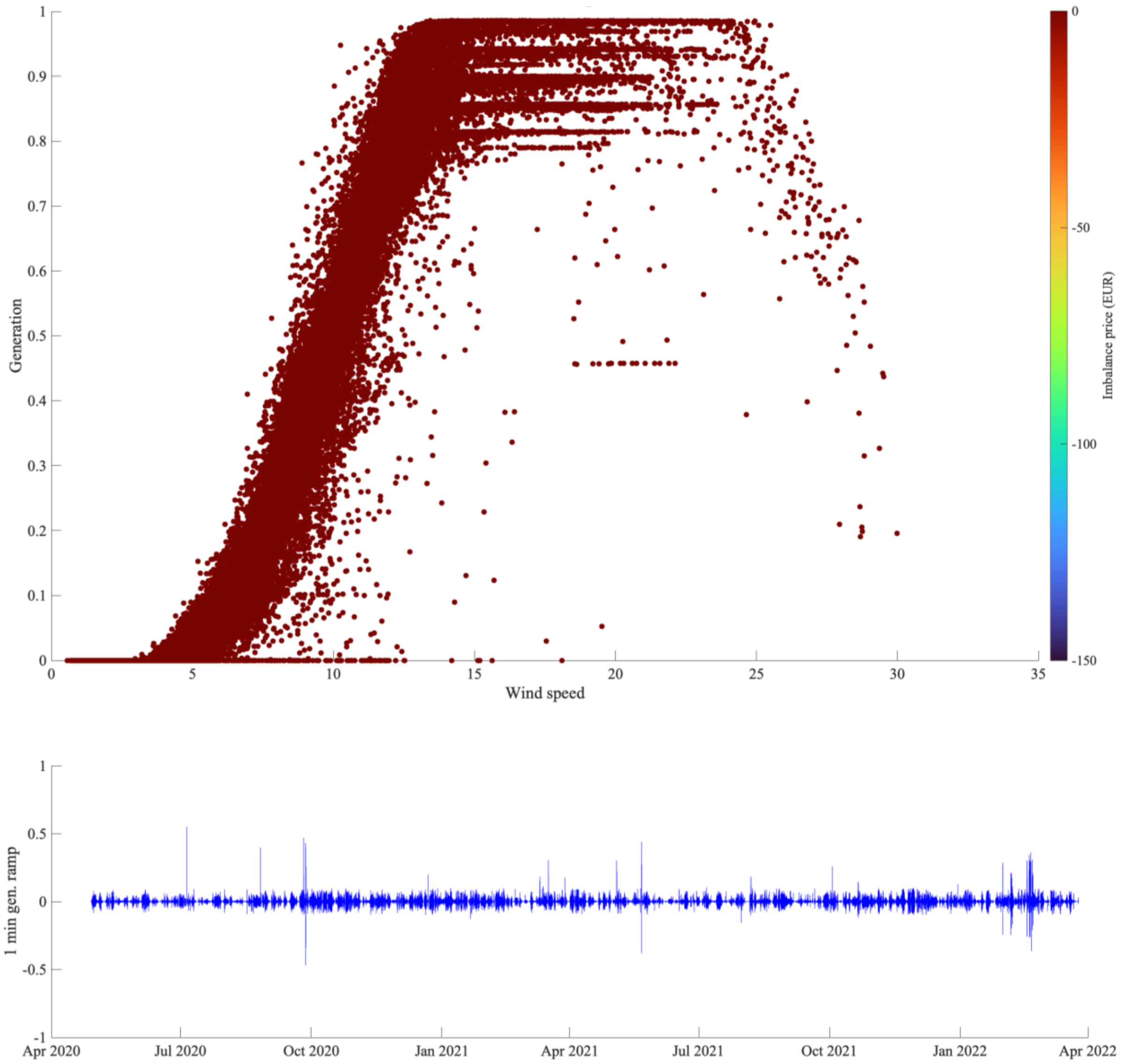

Figure 9. Measured wind speed and generation, and 1 min generation ramps after the filtering for the same example OWPP as in the previous figure. Colouring is based on negative imbalance price (prices below -150 EUR are shown with the same colour as -150 EUR). All generation data are in standardised generation (1 = full installed capacity).

5.2 Generation and wind speed time series validation

The following goes through the key validation metrics, and metrics where significant change was observed compared to the 2020 report. Other metrics show similar fit to the measured data as presented in the 2020 report. All generation data are in standardised generation (1 = full installed capacity).

5.2.1 Capacity factor and generation probability distribution

Figure 10 shows that the simulated and measured probability distributions (visualized as probability distribution functions, PDFs) are similar, expect for values between 0.85 and 1, which is expected as CorRES simulations do not consider unavailability (same as in the 2020 report). Note that the time range of measurements is longer than in the 2020 report. Even though information about unavailability of turbines was not available, an option to roughly consider the unavailability (and other losses than wake losses) in the simulations would be to multiple all simulated generation time series with a constant factor, e.g., 0.95. However, this would also cause the maximum generation to be reduced by 5 %. As can be seen in Figure 10, the measured data shows that sometimes the plant generation is close to full installed capacity. Thus, the multiplication by 0.95 was not applied, and all results are given assuming 100 % availability of the plants. Post-processing of the simulated time series assuming 100 % availability can be done later, if required, to assess the impact of losses other than wakes.

Capacity factor (CF) and standard deviation (SD) for the aggregate offshore wind generation of all the OWPPs in the 0.9 GW validation case are shown in Table 7. Both statistics are similar in the measured and simulated data. If additional losses (other than wake losses) would be around 5 % (3 % of unavailability and 2 % of other losses as presented in the literature [3]), the effective CF of the CorRES simulation would be 0.385, which is very close to the measured CF of 0.382.

CF and SD for the aggregate offshore wind generation of all the OWPPs in the 2.3 GW validation case are shown in Table 8. If the additional losses would be around 5 %, the effective CF of the CorRES simulation would be 0.367, which is still somewhat higher than the measured CF of 0.339. When looking at the generation profiles of the individual OWPPs, it was noticed that a few of them operated significantly beyond their installed capacity for significant time periods: an example can be seen in the scatter plot in Figure 9, where the plant operates at levels between 80 % to 100 % of installed capacity even when wind speeds are in the range from 13 m/s to 20 m/s. It is assumed that some of the plants in the 2.3 GW case operated at lower capacity than expected because they are recently commissioned. Thus, the difference between the simulated and measured CF is expected to be driven by higher-than-expected unavailability. Figure 11 shows that the simulated and measured PDFs are similar, expect for values between 0.85 and 1, which is expected as CorRES simulations do not consider unavailability.

Table 7. Capacity factor and standard deviation of the 0.9 GW validation case.

	CF	**SD**
Measured	0.382	0.343
Simulated	0.405	0.350

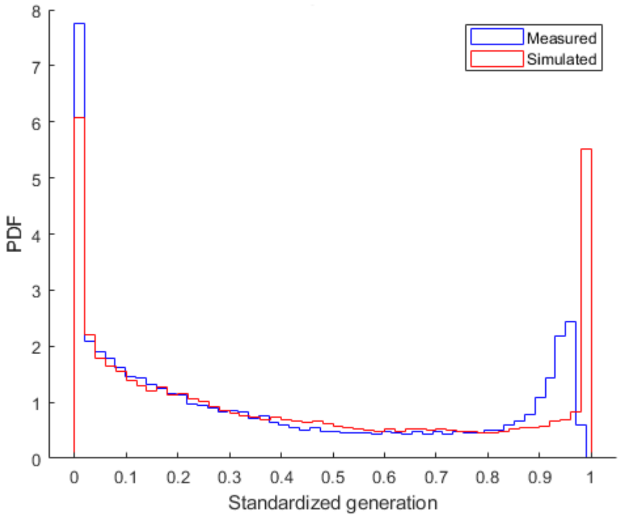

Figure 10. Generation distribution of the 0.9 GW validation case.

Table 8. Capacity factor and standard deviation of the 2.3 GW validation case.

	CF	SD
Measured	0.339	0.335
Simulated	0.386	0.353

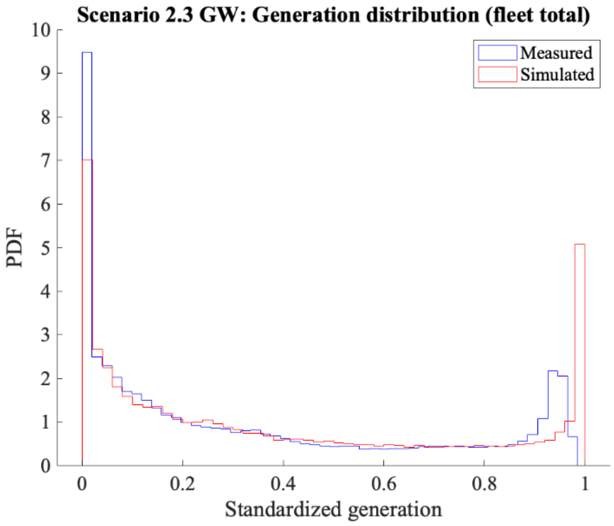

Figure 11. Generation distribution of the 2.3GW validation case.

5.2.2 Ramp behavior

The 5 min ramp behavior of the Belgian offshore wind fleet is shown in Figure 12 and Table 9 for the 0.9 GW validation case, and in Figure 13 and Table 10 for the 2.3 GW validation case. The ramp SDs are similar for the measured and simulated data for both cases. In the 0.9 GW case, the highest and lowest percentiles indicate slightly higher extreme ramps in the measured data than in the simulated data; however, in the 2.3 GW case, also the highest percentiles show a good fit.

The 15 min ramp behavior of the 0.9 GW and 2.3 GW case are shown in Figure 14 and Table 11, and in Figure 15 and Table 12, respectively. The simulated ramp SD is slightly lower in the 0.9 GW case but slightly higher in the 2.3 GW case compared to the measured data, indicating on average a good fit to the measurements. The most extreme percentiles (0.1 and 99.9) are somewhat closer to zero in the simulated data compared to the measurements, indicating that the simulation gives slightly lower likelihoods for the most extreme ramps. However, measured data can include events which are not in simulations, such as cable faults or control actions (in addition to the filtered ones), which can appear as ramp events. As the simulations do not include such events, it was not considered possible to assess the exact reason for the difference. The simulations are thus considered to be valid for simulating the ramp events; however, it needs to be noted that the likelihoods of the most extreme ramps may be slightly underestimated in the simulations. This is the same conclusion as in the 2020 report.

Similar information is given for 1 h ramps in Figure 16 and Table 13 for the 0.9 GW case, and in Figure 17 and Table 14 for the 2.3 GW case. The ramp SDs are on average similar in the simulated and measured data: in the 0.9 GW case the simulation shows a slightly lower SD and in the 2.3 GW case a slightly higher SD than the measurements. In the 0.9 GW case, the highest and lowest percentiles indicate slightly higher extreme ramps in the measured data than in the simulated data; however, in the 2.3 GW case, the highest percentiles are similar in the simulated and the measured data.

5 min ramps:

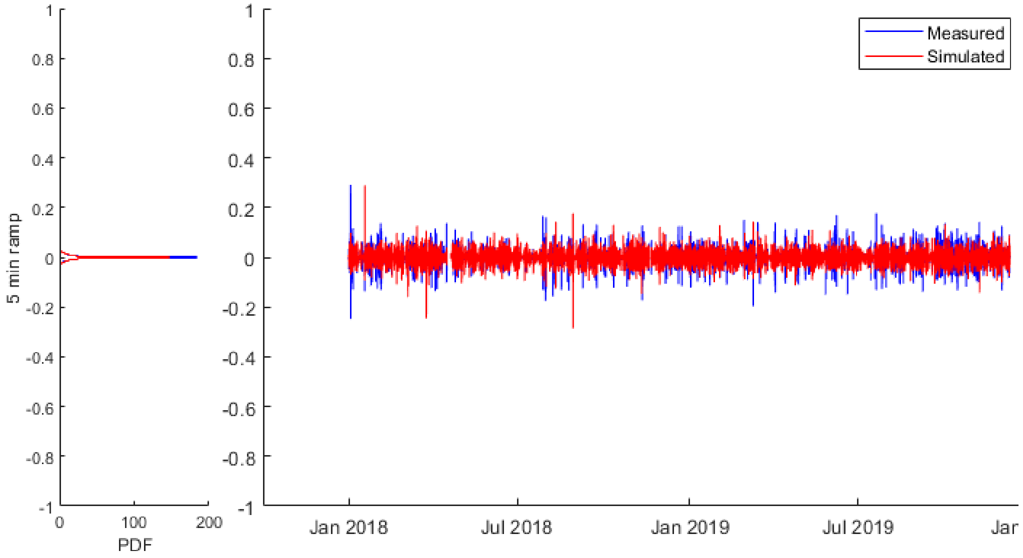

Figure 12. 5 min ramps in the 0.9 GW validation case.

Table 9. 5 min ramp statistics of the 0.9 GW validation case (Prct = percentile).

	Mean	SD	min	Prct 0.1	Prct 1	Prct 5	Prct 95	Prct 99	Prct 99.9	max
Measured	0.000	0.014	-0.247	-0.085	-0.040	-0.020	0.020	0.041	0.083	0.292
Simulated	0.000	0.013	-0.285	-0.063	-0.036	-0.020	0.020	0.036	0.062	0.290

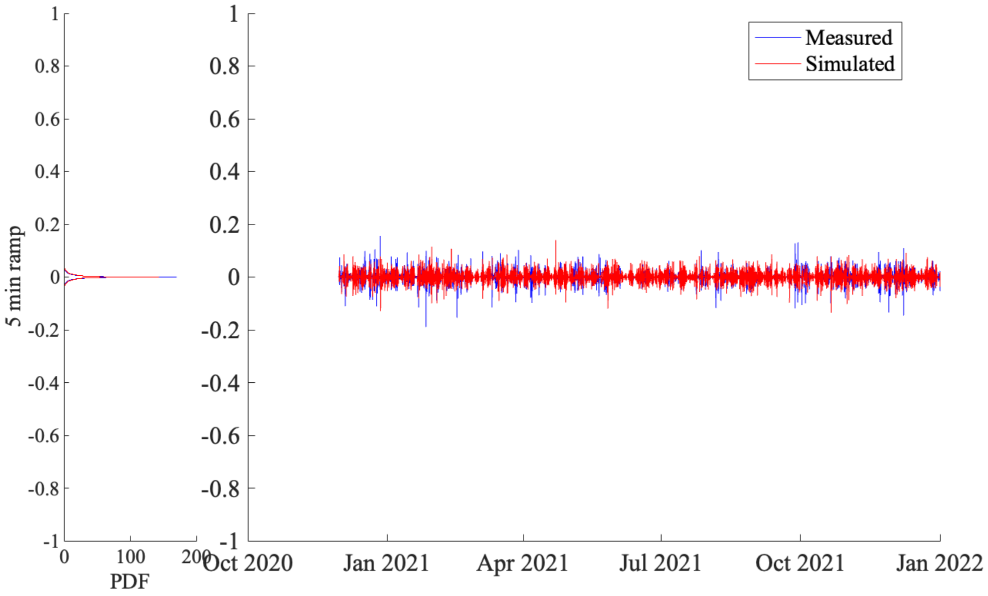

Figure 13. 5 min ramps in the 2.3 GW validation case.

Table 10. 5 min ramp statistics of the 2.3 GW validation case (Prct = percentile).

	Mean	SD	min	Prct 0.1	Prct 1	Prct 5	Prct 95	Prct 99	Prct 99.9	max
Measured	0.000	0.011	-0.189	-0.065	-0.032	-0.016	0.016	0.031	0.060	0.156
Simulated	0.000	0.011	-0.135	-0.057	-0.032	-0.018	0.018	0.033	0.058	0.140

15 min ramps:

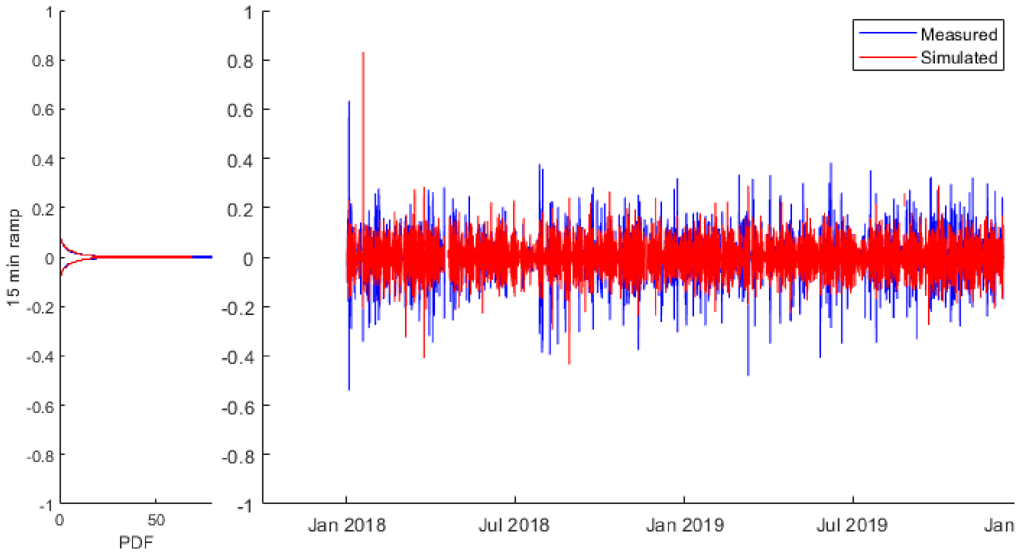

Figure 14. 15 min ramps in the 0.9 GW validation case.

Table 11. 15 min ramp statistics of BE 2018 (Prct = percentile).

	Mean	SD	min	Prct 0.1	Prct 1	Prct 5	Prct 95	Prct 99	Prct 99.9	max
Measured	0.000	0.033	-0.540	-0.209	-0.098	-0.049	0.050	0.102	0.199	0.634
Simulated	0.000	0.029	-0.435	-0.140	-0.084	-0.048	0.048	0.083	0.139	0.831

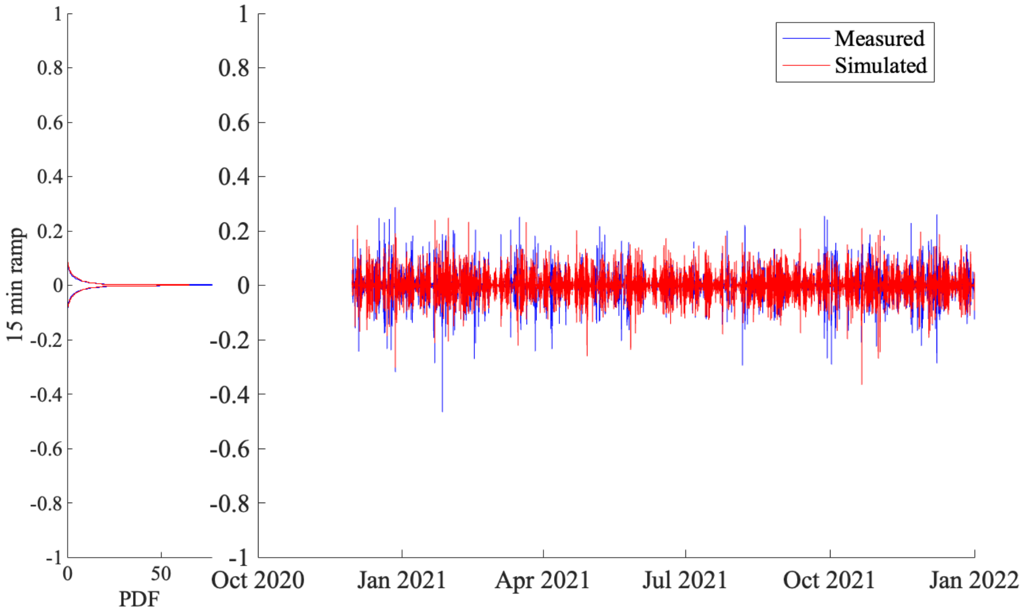

Figure 15. 15 min ramps in the 2.3 GW validation case.

Table 12. 15 min ramp statistics of the 2.3 GW validation case (Prct = percentile).

	Mean	SD	min	Prct 0.1	Prct 1	Prct 5	Prct 95	Prct 99	Prct 99.9	max
Measured	-0.001	0.027	-0.467	-0.161	-0.082	-0.041	0.040	0.080	0.153	0.287
Simulated	0.000	0.028	-0.365	-0.141	-0.079	-0.045	0.045	0.081	0.135	0.248

1 h ramps:

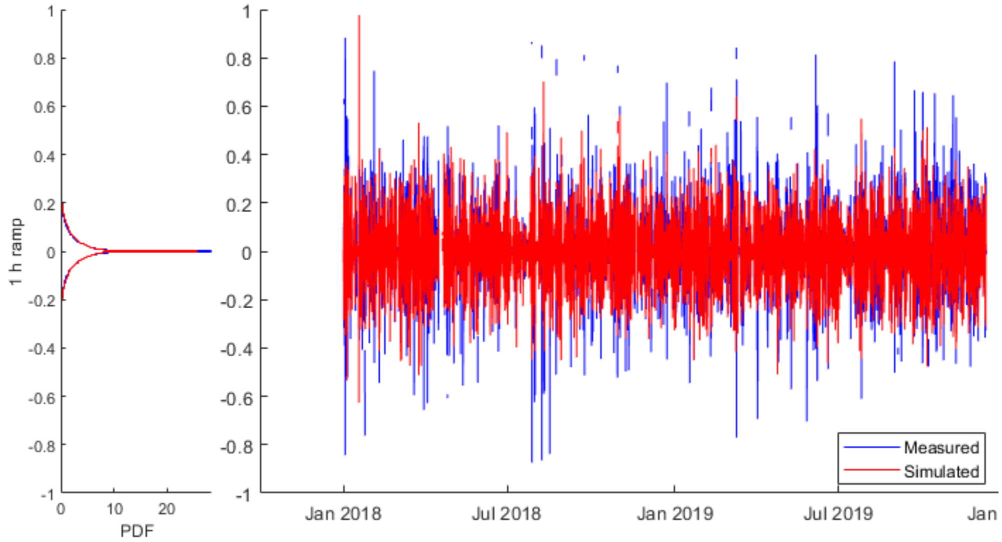

Figure 16. 1 h ramps in the 0.9 GW validation case.

Table 13. 1 h ramp statistics of the 0.9 GW validation case (Prct = percentile).

	Mean	SD	min	Prct 0.1	Prct 1	Prct 5	Prct 95	Prct 99	Prct 99.9	max
Measured	0.000	0.084	-0.874	-0.473	-0.241	-0.128	0.132	0.258	0.493	0.903
Simulated	0.000	0.076	-0.626	-0.353	-0.221	-0.125	0.125	0.217	0.360	0.976

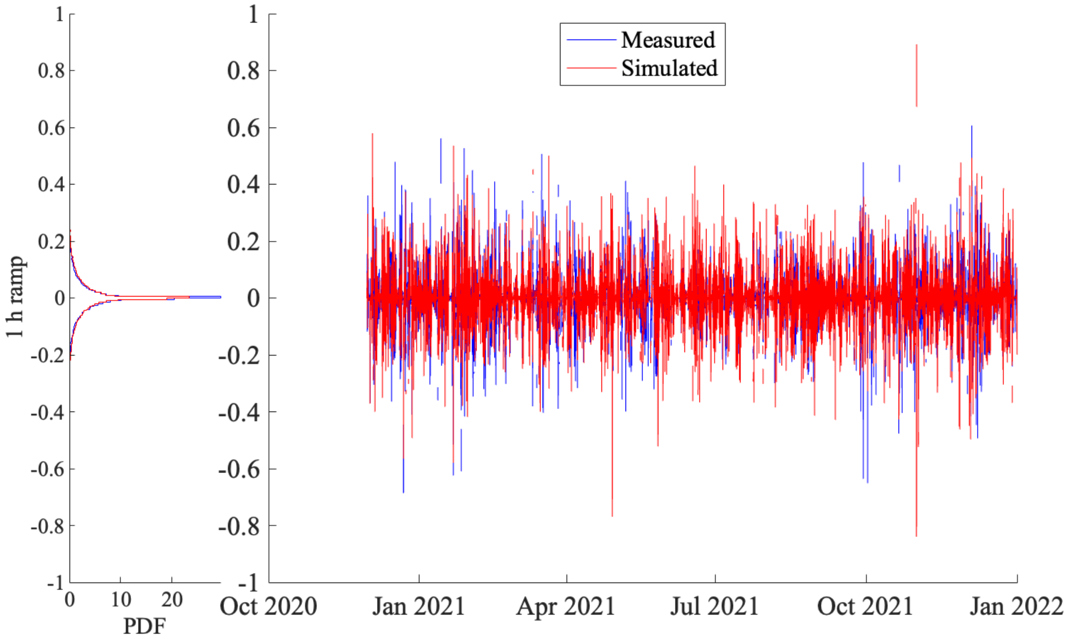

Figure 17. 1h ramps in the 2.3 GW validation case.

Table 14. 1 h ramp statistics of the 2.3 GW validation case (Prct = percentile).

	Mean	SD	min	Prct 0.1	Prct 1	Prct 5	Prct 95	Prct 99	Prct 99.9	max
Measured	-0.001	0.069	-0.686	-0.388	-0.208	-0.109	0.108	0.205	0.362	0.607
Simulated	0.000	0.077	-0.839	-0.415	-0.214	-0.125	0.124	0.225	0.367	0.892

5.2.3 High wind likelihoods and generation at different wind speeds

Statistics for very high percentiles of the measured and simulated wind speeds are show in Table 15 and Table 16 for the 0.9 GW and 2.3 GW case, respectively. Only the OWPPs with measured wind speeds are considered. The results show that while there are some differences between measured and simulated wind speeds for individual OWPPs, on average the simulations show a good fit to the measurements. The modeling of high wind speed events is carried out the same way as in the 2020 report.

The fleet-level wind speeds and the fleet-level generation behavior at different wind speeds are shown in Figure 18 and Figure 19 for the 0.9 GW and 2.3 GW case, respectively. The extreme wind speeds are similar for the measured and simulated data, and the generation behaves in a similar way both in the measured and the simulated data, with a complete fleet-level shutdown reached in the 0.9 GW case.

Table 15. Very high wind speed statistics for the 0.9 GW validation case.

	Percentile 99.9		**Percentile 99.99**		**max**	
	Measured	**Simulated**	**Measured**	**Simulated**	**Measured**	**Simulated**
OWPP 1	23.6	23.7	26.3	27.3	29.9	30.2
OWPP 2	25.3	23.3	28.9	28.2	33.2	30.5
OWPP 3	26.6	23.5	29.8	27.2	32.6	29.5
OWPP 4	24.7	24.3	27.2	29.0	29.4	30.1
Average	25.0	23.7	28.0	27.9	31.3	30.0

For the OWPPs with wind speed measurements from the periods with measurements available.

Table 16. Very high wind speed statistics for the 2.3 GW validation case.

	Percentile 99.9		**Percentile 99.99**		**max**	
	Measured	**Simulated**	**Measured**	**Simulated**	**Measured**	**Simulated**
OWPP A	26.0	26.5	28.1	29.8	29.3	32.3
OWPP B	25.4	26.4	29.2	29.8	32.6	32.4
OWPP C	24.8	22.9	27.3	25.0	29.6	27.9
OWPP D	24.4	23.3	27.2	24.5	30.0	26.5
OWPP E	26.2	26.9	28.1	29.3	28.6	29.6
Average	25.3	25.2	28.0	27.7	30.0	29.7

For the OWPPs with wind speed measurements from the periods with measurements available.

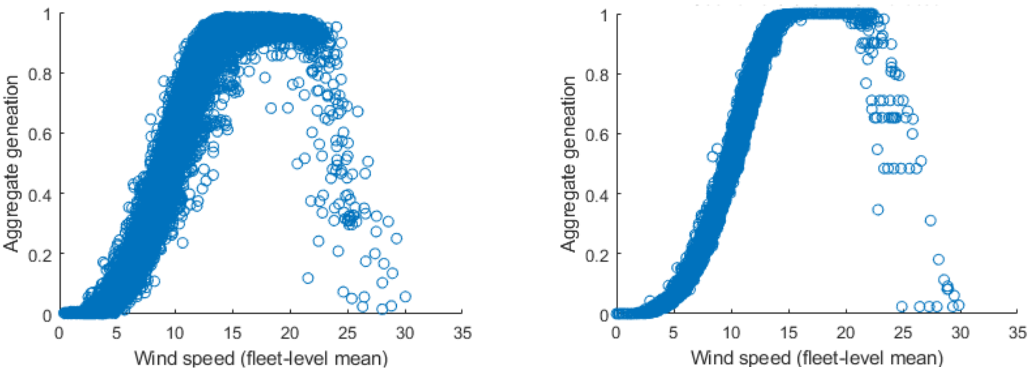

Figure 18. Measured (left) and simulated (right) wind speed and generation for the 0.9 GW validation case.

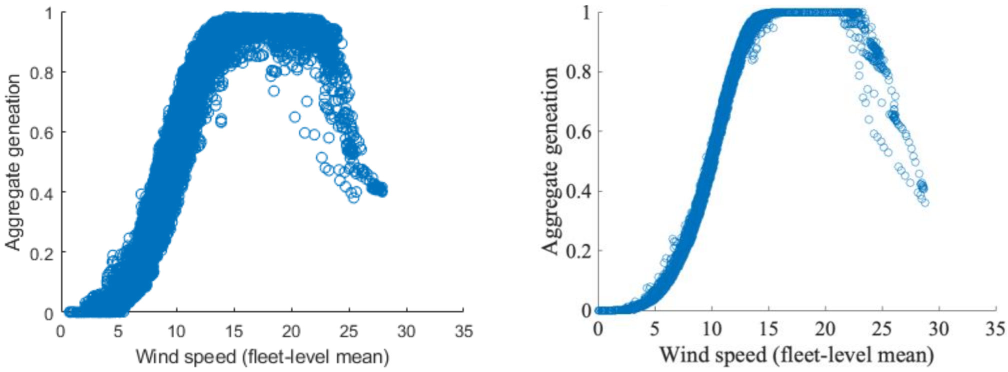

Figure 19. Measured (left) and simulated (right) wind speed and generation for the 2.3 GW validation case.

5.2.4 Correlation to measured generation

Using the ERA5 reanalysis data produces high correlation to measured data in simulation [3]. An example time range for the 2.3 GW case is plotted in Figure 20: the high and low wind events happen at the same time in the measured and simulated data. Correlation considering the whole measured time range is 0.95 for the 2.3 GW and 0.94 for the 0.9 GW case. These are significantly higher than the correlation of around 0.85 in the 2020 report. This means that in addition to the statistics presented in the previous sections, also the timings of events are well captured in the simulation. This allows the simulated data to be used together with other measured data, such as load, onshore wind, or solar generation time series.

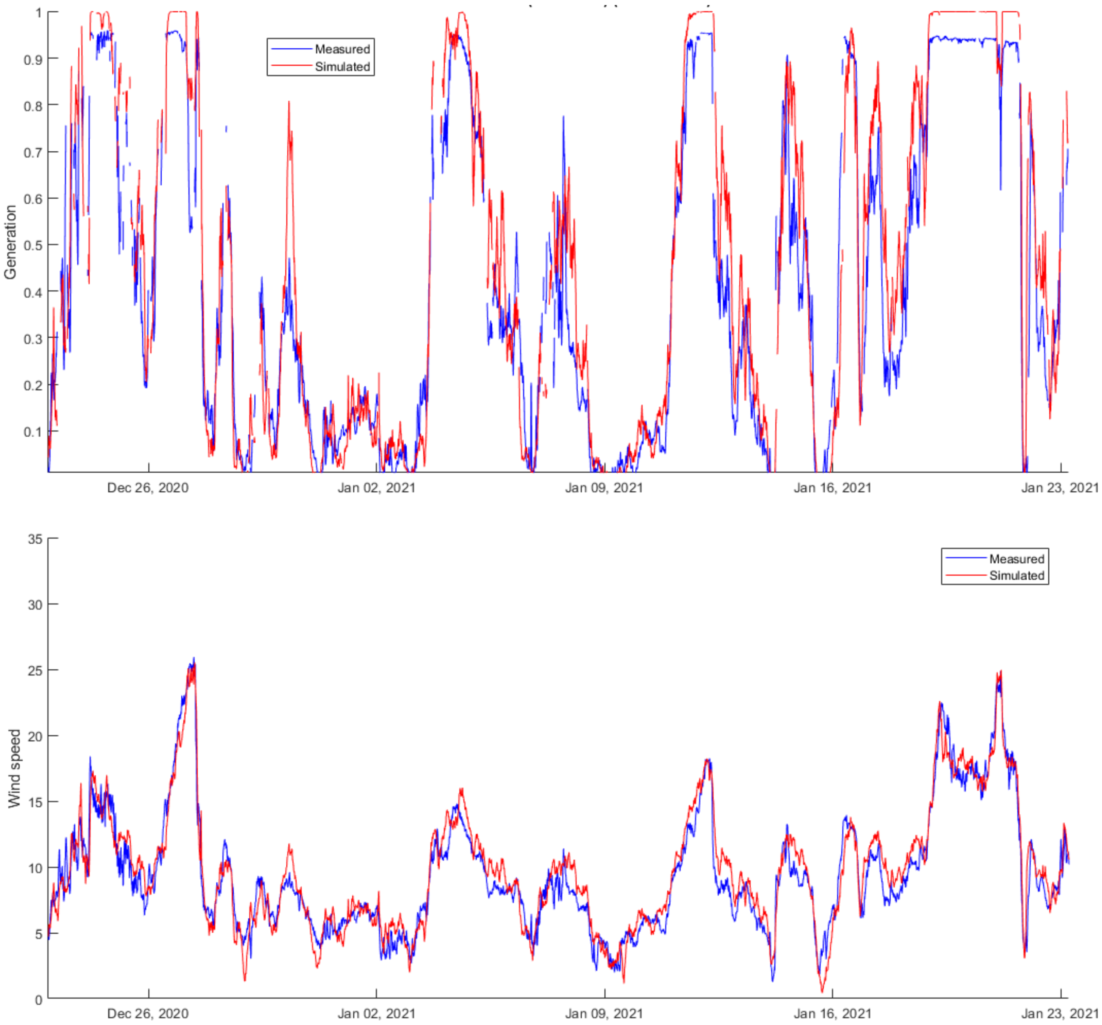

Figure 20. Example time range for the 2.3 GW validation case (all data are fleet-level means). The correlation between the simulated and measured generation (on 5 min resolution, for the entire time range with measurements) is 0.95.

5.3 Forecast error validation

The historical forecast observations are taken from Elia for a period from July 2017 to 2019 included in 15 min resolution. The forecast horizons day-ahead (DA), intraday, and Last are analysed, and using information from Elia on when the different horizons are updated, similar horizons are simulated in CorRES (same as in the 2020 report). Taking 15 min mean values, the measured 1 min generation data are transformed to 15 min resolution, after which historical forecast errors are calculated ($e_t = p_{t,actual} - p_{t,forecasted}$) for the three forecast horizons. For the simulations, 15 min mean values are taken from the simulated 5 min resolution time series, to reach comparable simulated forecast errors.

Measured and simulated day-ahead (DA), intraday, and Last forecast errors are shown for the 0.9 GW validation case in Figure 21. The distributions of the errors look similar and the SDs are similar in the measured and simulated data. However, for the Last forecasts, the simulation shows slightly lower uncertainty (i.e., lower forecast error SD) compared to the measurements. A similar conclusion was made in the 2020 report.

Further statistics are given in Table 17, Table 18 and Table 19. The root-mean-square error (RMSE) and mean-absolute-error (MAE) statistics confirm the conclusion as the SDs: the DA and intraday measured and simulated forecast errors are similar; for Last, the simulated data confirm the slightly lower uncertainty. For DA, the measured and simulated low and high percentiles are similar; however, the measured min and max forecast errors are larger than the simulated ones. For Intraday, the measured low and high percentiles are slightly larger (further from zero) than the simulated ones. For Last, as with SD, RMSE, MAE, and the percentiles show slightly lower uncertainty for simulation than for the measurements. It is noted that the measured data shows relatively small decrease in forecast error SD from Intraday to Last. In CorRES, this difference is larger.

The specification of the forecast simulation model is the same as in the 2020 report. However, as the forecast error is $e_t = p_{t,actual} - p_{t,forecasted}$, changes in the simulated $p_{t,actual}$ time series (driven by the model updates and updated meteorological data) cause slight changes also in the simulated forecast errors e_t. Compared to the 2020 report, the error SDs are now slightly closer to the measured forecast errors for DA and intraday, and about the same for Last.

In general, results show that the simulated forecast errors match well with the observations and the model can therefore be used to develop representative forecast errors for simulations on higher installed capacities up to 5.8 GW. Note that the validation exercise is only conducted for the 0.9 GW case and therefore for the period 2018 and 2019. Validation is not conducted for the 2.3 GW case and therefore for the period 2020 and 2021 as forecast accuracy of the Elia forecast tool was not considered fully representative during this period.

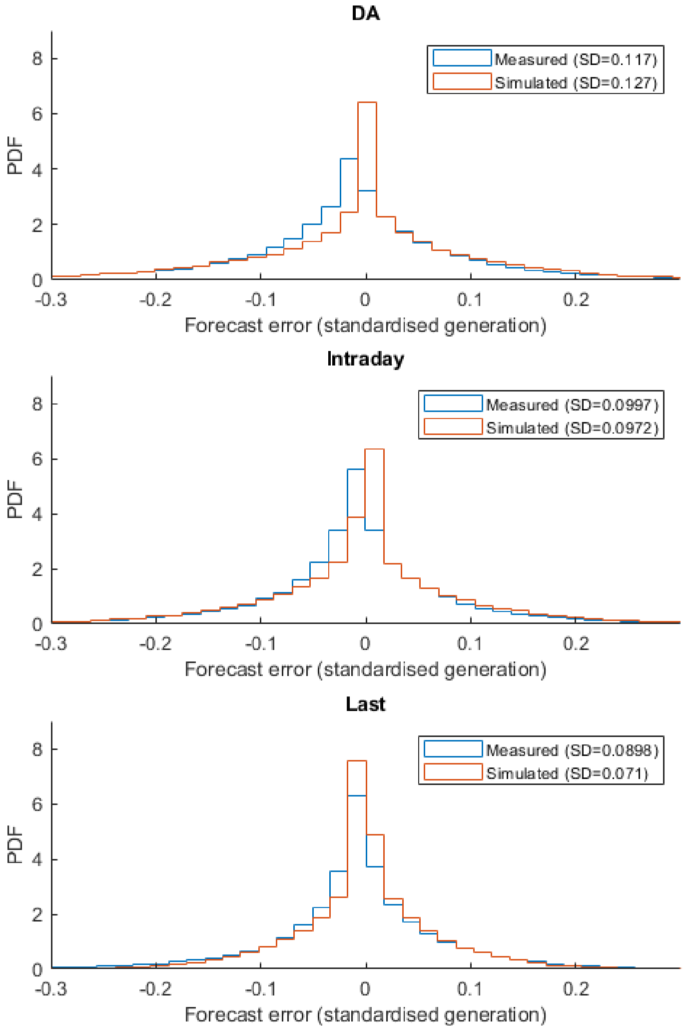

Figure 21. Forecast error distributions for the 0.9 GW validation case (SD=standard deviation; DA=day-ahead).

Table 17. Day-ahead forecast error statics for the 0.9 GW validation case (Prct = percentile).

	RMSE	**MAE**	**mean**	**SD**	**min**	**Prct 0.1**	**Prct 1**	**Prct 5**	**Prct 95**	**Prct 99**	**Prct 99.9**	**max**
Measured	0.118	0.080	-0.013	0.117	-0.932	-0.555	-0.353	-0.210	0.177	0.319	0.511	0.815
Simulated	0.127	0.084	-0.004	0.127	-0.747	-0.535	-0.369	-0.221	0.201	0.366	0.549	0.767

Table 18. Intraday forecast error statics for the 0.9 GW validation case (Prct = percentile).

	RMSE	**MAE**	**mean**	**SD**	**min**	**Prct 0.1**	**Prct 1**	**Prct 5**	**Prct 95**	**Prct 99**	**Prct 99.9**	**max**
Measured	0.100	0.066	-0.011	0.100	-0.932	-0.534	-0.317	-0.176	0.146	0.266	0.465	0.792
Simulated	0.097	0.065	-0.002	0.097	-0.614	-0.412	-0.275	-0.171	0.159	0.274	0.396	0.553

Table 19. Last forecast error statics for the 0.9 GW validation case (Prct = percentile).

	RMSE	**MAE**	**mean**	**SD**	**min**	**Prct 0.1**	**Prct 1**	**Prct 5**	**Prct 95**	**Prct 99**	**Prct 99.9**	**max**
Measured	0.090	0.059	-0.008	0.090	-0.932	-0.485	-0.282	-0.158	0.133	0.237	0.419	0.765
Simulated	0.071	0.047	-0.001	0.071	-0.621	-0.320	-0.203	-0.120	0.118	0.197	0.300	0.572

5.4 Conclusion on the model validation

The model validation shows that CorRES can model the generation time series of the existing offshore wind power plants in Belgium (the 0.9 GW and the 2.3 GW case) with an acceptable accuracy. It is thus considered valid for modelling the MOG II capacity extension.

The capacity factors predicted by CorRES are slightly higher than measured, because the simulations assume 100 % availability (same as in the 2020 report). When assuming a 5 % unavailability for the 0.9 GW case, the measured and simulated capacity factor are very similar. Note that the observed results for the 2.3 GW case show higher unavailability than usual (5 %), increasing the deviation from the simulations.

Statistics of ramps are similar for the measured and simulated data. There is a slight underestimation of the 0.1 and 99.9 percentiles for the 0.9 GW case; this means that the likelihoods of the events rarer than the 0.1 and 99.9 percentile range may be underestimated in CorRES. However, the simulated data are not adjusted, because the reason for these differences cannot be clearly identified. On the other hand, for the 2.3 GW case also the 0.1 and 99.9 percentiles are overall well modelled. However, the uncertainty in modelling the most extreme ramp likelihoods needs to be noted when assessing the results of the simulations for higher installed capacities up to 5.8 GW.

The simulations model well the likelihoods of very high wind speeds, and the behaviour of the generation during high wind events. The use of 40 years of meteorological data in simulations for higher installed capacities ensures that a wide range of extreme events are simulated.

For forecast errors, CorRES simulations show similar statistics compared to observations. However, for the Last forecast, CorRES shows slightly lower uncertainty than the observation. In general, forecast errors are more difficult to simulate, as the target is not to replicate the variability due to weather, but to try to represent the forecasts by the Elia’s forecast provider. For this reason, the results presented for forecasts and forecast errors for the extended capacity scenarios need to be taken as representing average changes in the forecast errors resulting from different geographical installation distributions and storm shutdown technologies. The actual simulated forecast and forecast error values for an individual event are stochastic and can be high or low due to randomness.

6. Basic statistics for the scenarios

Capacity factors (CF) and Standard Deviations (SD) of the aggregate generation of the entire fleet in the different scenarios are given in Table 20. Note that at following the focus of the study, unavailability and other losses than wake losses are not modelled (see also Section 5.2.1). The CF of the aggregated fleet is expected to increase from today towards the 5.8 GW scenarios, with Tech B showing significant increase compared to Tech A. The higher CFs are driven by higher hub heights (and thus higher wind speeds) and lower specific power turbines (and thus more generation at lower wind speeds) in Tech B compared to Tech A (see Table 1 and Table 2). This implies a higher annual offshore generation with the same installed capacity. As storm events are relatively rare, there are only very small differences between the different storm shutdown types. Table 21 shows the same statistics for the additional installations (coming on top of the existing 2.3 GW).

The resulting wake losses (which also include blockage losses) of 11.2% - 12.0% in this study for the additional installations in the 5.8 GW scenario (i.e., 3.5 GW of additional installations) are similar to the recent study published by 3E [2], where the most similar technology (17MW_Generic) show a combined wake and blockage loss of 11.9% for the comparable scenario. The other scenarios are not easily comparable, as the geographical distributions of the installations are not the same.

Table 20. Capacity factors and standard deviations (entire fleet).

			CF	**SD**	**CF compared to 0.9 GW**	**SD compared to 0.9 GW**
0.9 GW			0.420	0.355	100%	100%
2.3 GW			0.425	0.365	101%	103%
3.0 GW	**Tech A**	**25 m/s**	0.433	0.364	103%	103%
		Moderate	0.433	0.365	103%	103%
		Deep	0.433	0.365	103%	103%
	Tech B	**25 m/s**	0.447	0.365	106%	103%
		Moderate	0.447	0.366	106%	103%
		Deep	0.448	0.366	107%	103%
4.4 GW	**Tech A**	**25 m/s**	0.436	0.363	104%	102%
		Moderate	0.437	0.363	104%	102%
		Deep	0.437	0.364	104%	102%
	Tech B	**25 m/s**	0.466	0.367	111%	103%
		Moderate	0.467	0.368	111%	104%
		Deep	0.468	0.368	111%	104%
5.8 GW	**Tech A**	**25 m/s**	0.436	0.362	104%	102%
		Moderate	0.437	0.363	104%	102%
		Deep	0.438	0.363	104%	102%
	Tech B	**25 m/s**	0.472	0.369	112%	104%
		Moderate	0.474	0.370	113%	104%
		Deep	0.475	0.370	113%	104%

From the 40 years of simulations on 5 min resolution. Only wake losses are considered (availability of 100% is assumed).

In Table 20, the SD increases only slightly towards the 5.8 GW scenarios, with Tech B showing marginally higher SD than Tech A. Overall, the simulated SDs are slightly higher than in the 2020 report; this is due to higher hub heights (both in Tech A an Tech B) and model and weather data updates.

Table 21. Capacity factors and standard deviations (additional installations).

			CF	SD	CF compared to 0.9 GW	SD compared to 0.9 GW
3.0 GW (0.7 GW)	**Tech A**	**25 m/s**	0.458	0.370	109%	104%
		Moderate	0.460	0.370	110%	104%
		Deep	0.461	0.370	110%	104%
	Tech B	**25 m/s**	0.518	0.382	123%	108%
		Moderate	0.521	0.382	124%	108%
		Deep	0.523	0.382	124%	108%
4.4 GW (2.1 GW)	**Tech A**	**25 m/s**	0.448	0.365	107%	103%
		Moderate	0.450	0.366	107%	103%
		Deep	0.451	0.366	107%	103%
	Tech B	**25 m/s**	0.510	0.379	121%	107%
		Moderate	0.513	0.379	122%	107%
		Deep	0.514	0.379	122%	107%
5.8 GW (3.5 GW)	**Tech A**	**25 m/s**	0.443	0.365	105%	103%
		Moderate	0.445	0.365	106%	103%
		Deep	0.446	0.365	106%	103%
	Tech B	**25 m/s**	0.503	0.379	120%	107%
		Moderate	0.505	0.379	120%	107%
		Deep	0.506	0.379	120%	107%

From the 40 years of simulations on 5 min resolution. Only wake losses are considered (availability of 100% is assumed). The GW values in the brackets show the capacity of the additional installations.

7. Statistical analysis of ramp events

This chapter presents the results on ramping events for the studied scenarios. As with all the scenario results, they are based on the 40 years of simulations from 1982 to 2021, simulated on 5 min resolution. Each OWPP is simulated, although only aggregated ramp results are reported. All results are given based on 5 min resolution data.

The first section compares the scenarios in standardized generation, as the impact of geographical smoothening is easier to see when all data are standardized. Section 7.2 shows the results in GW. It is to be noted that the storm events are not filtered out of the data in these analyses, which means that the ramps that occur during the cut-out and the cut-in phases of storms is included in the statistics presented. To isolate the ramp events which are not due to storms, Section 7.3 shows the same results but only for those days when the maximum daily wind speed is below 20 m/s.

7.1 Ramps in standardized generation

7.1.1 5 min ramps

Figure 22 shows 5 min ramp distributions for some example scenarios. The 5 min ramps, expressed in standardized generation, decrease from the 0.9 GW scenario towards the 5.8 GW scenarios. As in the 2020 report, the 5 min ramps (compared to the 15 min and 1 h ramps) show the biggest differences between the scenarios. The differences are driven by geographical smoothening. The different storm shutdown types show very similar distributions because storm events are relatively rare, and the differences between the different storm shutdown types impact only the most extreme tails of the distributions.

The 5 min ramp statistics of all the scenarios are shown in Table 22. The ramp SD decreases from the 0.9 GW scenario towards the 5.8 GW scenarios, driven by geographical smoothening. The Deep and Moderate storm shutdown types show decreased likelihoods for the most extreme ramps compared to the 25 m/s cut-off; the relative difference is even larger for the 5.8 GW scenarios than for the 4.4 GW scenarios. Tech B shows very slightly higher ramps than Tech A. The modest differences compared to the 2020 report for the 0.9 GW and 2.3 GW scenarios are due to updated modelling and meteorological data.

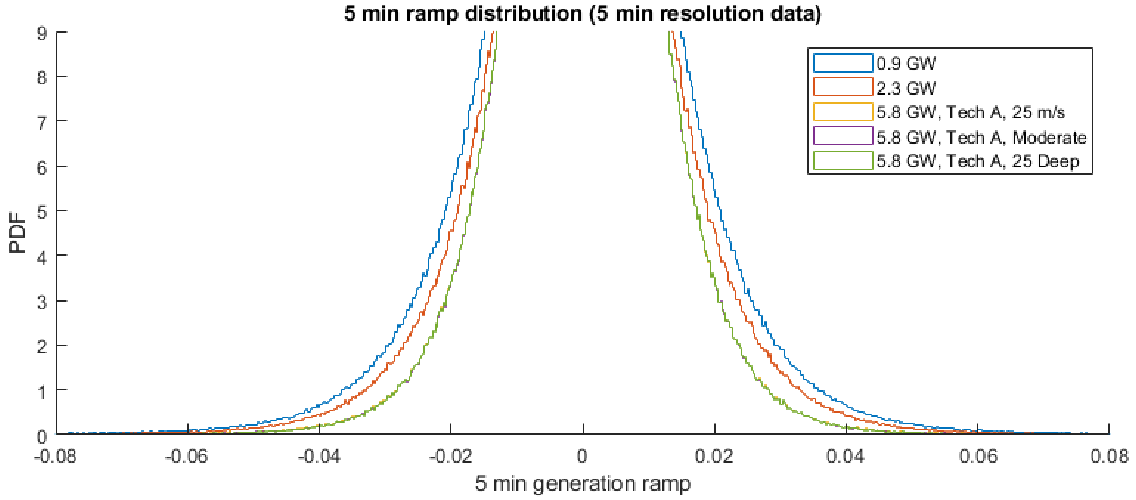

Figure 22. 5 min ramp distributions for example scenarios (standardized generation). The 5.8 GW scenarios with different storm shutdown types are almost fully on top of each other.

Table 22. 5 min ramps statistics (standardized generation).

								Compared to 0.9 GW		
			SD	**Prct 0.01**	**Prct 0.1**	**Prct 99.9**	**Prct 99.99**	**SD**	**Prct 0.1**	**Prct 99.9**
0.9 GW			0.013	-0.106	-0.064	0.066	0.115	100%	100%	100%
2.3 GW			0.011	-0.087	-0.054	0.056	0.090	86%	85%	85%
3.0 GW	**Tech A**	**25 m/s**	0.010	-0.083	-0.051	0.052	0.087	81%	80%	79%
		Moderate	0.010	-0.082	-0.051	0.052	0.086	80%	79%	78%
		Deep	0.010	-0.080	-0.050	0.051	0.083	80%	79%	78%
	Tech B	**25 m/s**	0.010	-0.085	-0.052	0.052	0.087	81%	82%	79%
		Moderate	0.010	-0.085	-0.051	0.052	0.086	81%	81%	79%
		Deep	0.010	-0.081	-0.051	0.051	0.084	81%	80%	78%
4.4 GW	**Tech A**	**25 m/s**	0.009	-0.085	-0.046	0.047	0.087	74%	72%	72%
		Moderate	0.009	-0.076	-0.044	0.046	0.080	73%	70%	70%
		Deep	0.009	-0.069	-0.044	0.045	0.075	72%	69%	69%
	Tech B	**25 m/s**	0.010	-0.088	-0.048	0.048	0.089	76%	76%	73%
		Moderate	0.010	-0.079	-0.047	0.047	0.084	75%	73%	71%
		Deep	0.009	-0.072	-0.046	0.046	0.077	74%	72%	70%
5.8 GW	**Tech A**	**25 m/s**	0.009	-0.089	-0.044	0.046	0.090	72%	70%	70%
		Moderate	0.009	-0.075	-0.043	0.045	0.080	71%	67%	68%
		Deep	0.009	-0.067	-0.042	0.044	0.073	70%	66%	67%
	Tech B	**25 m/s**	0.010	-0.094	-0.048	0.049	0.097	75%	75%	74%
		Moderate	0.009	-0.079	-0.046	0.047	0.085	73%	71%	71%
		Deep	0.009	-0.072	-0.045	0.046	0.076	73%	70%	69%

7.1.2 15 min ramps

Figure 23 shows 15 min ramp distributions of example scenarios. The 15 min ramps statistics of all the scenarios are shown in Table 23. As with the 5 min ramps, the 15 ramp SD decreases from the 0.9 GW scenario to the 5.8 GW scenarios, however, the relative reduction is less. The Deep and Moderate storm shutdown types show decreased likelihoods for the most extreme ramps compared to the 25 m/s cut-off. Tech B shows very slightly higher ramps than Tech A. The modest differences compared to the 2020 report for the 0.9 GW and 2.3 GW scenarios are due to updated modelling and meteorological data.

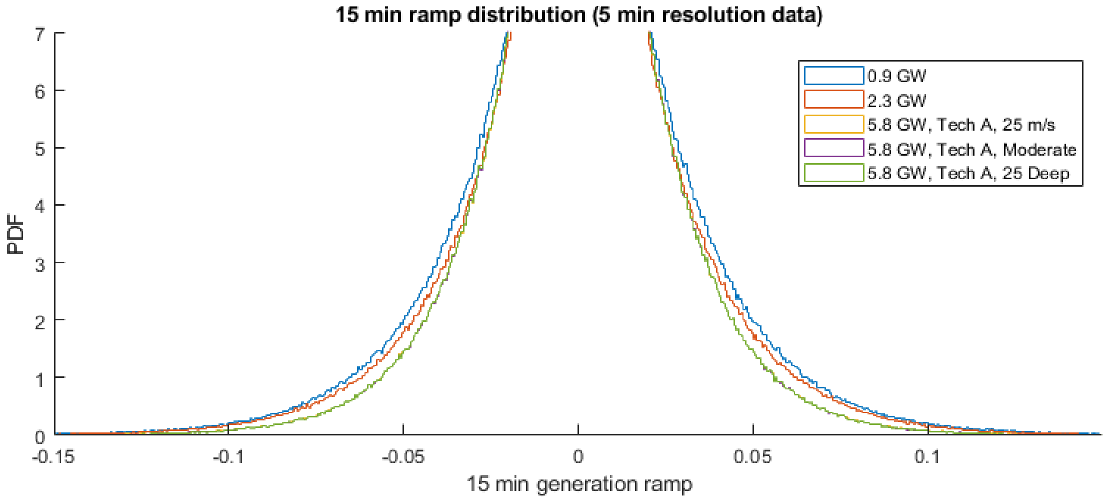

Figure 23. 15 ramp distributions for example scenarios (standardized generation). The 5.8 GW scenarios with different storm shutdown types are almost fully on top of each other.

Table 23. 15 min ramp statistics (standardized generation).

								Compared to 0.9 GW		
			SD	**Prct 0.01**	**Prct 0.1**	**Prct 99.9**	**Prct 99.99**	**SD**	**Prct 0.1**	**Prct 99.9**
0.9 GW			0.029	-0.221	-0.141	0.148	0.248	100%	100%	100%
2.3 GW			0.027	-0.200	-0.131	0.137	0.214	93%	93%	93%
3.0 GW	**Tech A**	**25 m/s**	0.026	-0.195	-0.124	0.129	0.210	87%	88%	87%
		Moderate	0.025	-0.195	-0.123	0.128	0.209	87%	88%	87%
		Deep	0.025	-0.186	-0.122	0.127	0.200	87%	87%	86%
	Tech B	**25 m/s**	0.026	-0.196	-0.126	0.128	0.206	88%	89%	87%
		Moderate	0.026	-0.197	-0.125	0.127	0.207	88%	89%	86%
		Deep	0.026	-0.188	-0.124	0.126	0.200	87%	88%	85%
4.4 GW	**Tech A**	**25 m/s**	0.024	-0.202	-0.115	0.119	0.220	81%	81%	81%
		Moderate	0.024	-0.176	-0.111	0.116	0.199	81%	79%	79%
		Deep	0.023	-0.161	-0.110	0.114	0.183	80%	78%	77%
	Tech B	**25 m/s**	0.024	-0.210	-0.120	0.121	0.220	83%	85%	82%
		Moderate	0.024	-0.188	-0.117	0.118	0.204	83%	83%	80%
		Deep	0.024	-0.168	-0.114	0.115	0.185	82%	81%	78%
5.8 GW	**Tech A**	**25 m/s**	0.024	-0.224	-0.114	0.119	0.235	81%	81%	81%
		Moderate	0.023	-0.187	-0.109	0.115	0.205	80%	77%	78%
		Deep	0.023	-0.159	-0.107	0.112	0.182	79%	76%	76%
	Tech B	**25 m/s**	0.024	-0.236	-0.123	0.125	0.244	84%	87%	85%
		Moderate	0.024	-0.195	-0.117	0.120	0.218	82%	83%	81%
		Deep	0.024	-0.171	-0.114	0.117	0.189	81%	81%	79%

7.1.3 1 h ramps

Figure 24 shows 1h ramp distributions for example scenarios: the 1 h ramps (in standardized generation) decrease from the 0.9 GW scenario towards the 5.8 GW of installations; however, the relative decrease in variability is significantly less than for the 5 min and 15 min ramps (as noted also in the 2020 report). 1 h ramp statistics of all the scenarios are shown in Table 24. The Deep and Moderate storm shutdown types show only slightly decreased likelihoods for the most extreme ramps compared to the 25 m/s cut-off in the 4.4 GW scenarios (like the 2020 report); however, in the 5.8 GW scenarios, especially the Deep type shows significantly reduced extreme negative ramps. The ramp distributions tend to be skewed slightly to the right (meaning that there are more extreme up-ramps than down-ramps), especially for the Deep type. This is driven by the difference in how the OWPPs operate at shutdown versus at the return from a storm; a more detailed explanation is given in Section 8.4. Tech B shows very slightly higher ramps than Tech A. The modest differences compared to the 2020 report for the 0.9 GW and 2.3 GW scenarios are due to updated modelling and meteorological data

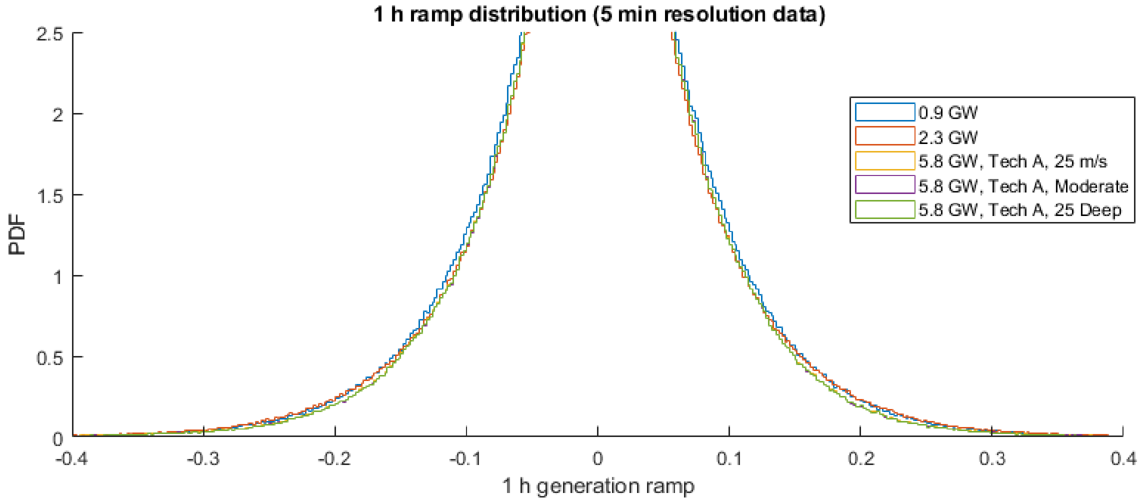

Figure 24. 1h ramp PDFs for example scenarios (standardized generation). The 5.8 GW scenarios with different storm shutdown types are almost fully on top of each other.

Table 24. 1 h ramp statistics (standardized generation).

								Compared to 0.9 GW		
			SD	**Prct 0.01**	**Prct 0.1**	**Prct 99.9**	**Prct 99.99**	**SD**	**Prct 0.1**	**Prct 99.9**
0.9 GW			0.076	-0.506	-0.350	0.381	0.644	100%	100%	100%
2.3 GW			0.075	-0.493	-0.354	0.380	0.595	100%	101%	100%
3.0 GW	**Tech A**	**25 m/s**	0.073	-0.473	-0.343	0.372	0.564	97%	98%	98%
		Moderate	0.073	-0.481	-0.344	0.372	0.569	97%	98%	98%
		Deep	0.073	-0.472	-0.340	0.368	0.562	97%	97%	97%
	Tech B	**25 m/s**	0.074	-0.479	-0.344	0.367	0.545	98%	98%	96%
		Moderate	0.074	-0.485	-0.346	0.368	0.551	97%	99%	97%
		Deep	0.073	-0.481	-0.343	0.364	0.551	97%	98%	96%
4.4 GW	**Tech A**	**25 m/s**	0.071	-0.513	-0.339	0.365	0.574	95%	97%	96%
		Moderate	0.071	-0.486	-0.328	0.354	0.571	94%	94%	93%
		Deep	0.070	-0.446	-0.322	0.347	0.532	93%	92%	91%
	Tech B	**25 m/s**	0.073	-0.506	-0.351	0.367	0.553	97%	100%	96%
		Moderate	0.072	-0.502	-0.342	0.357	0.577	96%	97%	94%
		Deep	0.072	-0.465	-0.333	0.349	0.524	95%	95%	92%
5.8 GW	**Tech A**	**25 m/s**	0.072	-0.573	-0.345	0.374	0.633	95%	98%	98%
		Moderate	0.071	-0.504	-0.328	0.359	0.603	94%	94%	94%
		Deep	0.070	-0.447	-0.318	0.348	0.536	93%	91%	91%
	Tech B	**25 m/s**	0.074	-0.583	-0.369	0.387	0.625	98%	105%	102%
		Moderate	0.073	-0.522	-0.347	0.368	0.626	96%	99%	97%
		Deep	0.072	-0.471	-0.337	0.358	0.556	96%	96%	94%

7.2 Ramps in GW

This section describes the ramp rate results in GW. The data are presented looking at the average number of days per year with at least one ramp event more extreme than a given value expressed in GW.

7.2.1 5 min ramps

Table 25 shows the ramp results in GW for 5 min ramps. The differences between the scenarios are the same as discussed in Section 7.1.1, but here the scenarios with more installed GW of course show more extreme ramps. The ability of the Deep shutdown type to reduce extreme 5 min ramps is significant in both the 4.4 GW and 5.8 GW scenarios. For the 5.8 GW Tech B scenario, the Deep type shows larger than 1 GW negative ramps in less than 1 day in 10 years, whereas the 25 m/s cut-off shows them almost every year.

Table 25. 5 min ramps: average number of days per year with at least one event more extreme than the limit.

			Negative Ramp (GW)												Positive Ramp (GW)											
			5.5	5.0	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0	0.5	0.3	0.3	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5
0.9 GW															0.05											
2.3 GW														1.2	0.88	0.08										
3.0 GW	Tech A	25 m/s										0.03	0.45	3.2	4.5	0.38	0.05									
		Moderate											0.20	3.4	4.1	0.33	0.03									
		Deep											0.05	2.2	3.4	0.25	0.03									
	Tech B	25 m/s											0.45	3.8	4.4	0.43	0.05									
		Moderate											0.38	3.9	4.2	0.35	0.05									
		Deep											0.08	2.7	3.4	0.28	0.03									
4.4 GW	Tech A	25 m/s										0.30	3.0	13	14	2.9	0.45	0.03								
		Moderate										0.08	1.7	11	12	2.0	0.20	0.03								
		Deep											0.7	8	10	1.2	0.05	0.03								
	Tech B	25 m/s										0.40	3.5	16	16	3.1	0.35	0.03								
		Moderate										0.10	2.5	13	13	2.7	0.33	0.03								
		Deep											1.0	11	12	1.5	0.08									
5.8 GW	Tech A	25 m/s									0.13	0.83	7.0	30	32	6.0	0.73	0.03								
		Moderate										0.38	4.7	26	28	4.3	0.58	0.15	0.05							
		Deep											2.7	24	27	2.7	0.23	0.08	0.03							
	Tech B	25 m/s								0.03	0.10	0.93	8.6	39	41	8.0	0.73	0.05								
		Moderate									0.05	0.40	5.4	34	36	5.7	0.70	0.23	0.03							
		Deep										0.05	3.5	32	34	3.8	0.38	0.10	0.05							

7.2.2 15 min ramps

Table 26 shows results in GW for the 15 min ramps. The differences between the scenarios are the same as discussed in Section 7.1.2, but here the scenarios with more installed GW of course show more extreme ramps. The benefit of the Deep type in reducing the most extreme negative ramps is very significant in both the 4.4 GW and 5.8 GW scenarios.

Table 26. 15 min ramps: average number of days per year with at least one event more extreme than the limit.

			Negative Ramp (GW)												Positive Ramp (GW)											
			5.5	5.0	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0	0.5	0.3	0.3	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5
0.9 GW														0.93	1.2	0.23										
2.3 GW													3.9	46	51	4.7	0.15	0.05	0.03							
3.0 GW	Tech A	25 m/s										0.10	11	97	101	13	0.35	0.10	0.03	0.03						
		Moderate										0.10	11	95	99	13	0.35	0.10	0.05							
		Deep										0.03	9.5	94	98	11	0.28	0.08	0.03							
	Tech B	25 m/s										0.13	13	102	101	13	0.33	0.10	0.03							
		Moderate										0.10	13	99	99	13	0.35	0.10	0.05	0.03						
		Deep										0.05	11	98	97	11	0.33	0.10	0.05							
4.4 GW	Tech A	25 m/s								0.03	0.50	3.0	39	190	194	42	3.5	0.73	0.23	0.10	0.05	0.03				
		Moderate								0.05	0.28	1.9	36	188	192	39	2.4	0.55	0.25	0.13	0.03	0.03				
		Deep										0.83	34	187	191	38	1.5	0.28	0.10	0.03						
	Tech B	25 m/s								0.03	0.55	3.7	48	202	204	47	3.8	0.63	0.20	0.08	0.08					
		Moderate								0.05	0.38	2.5	45	199	200	44	2.7	0.83	0.33	0.13	0.05	0.03				
		Deep										1.1	43	198	199	42	1.7	0.35	0.25	0.05						
5.8 GW	Tech A	25 m/s						0.08	0.33	1.0	2.6	8.3	98	254	256	106	8.5	2.8	1.1	0.50	0.23	0.10	0.03			
		Moderate							0.05	0.33	1.4	5.7	95	251	254	103	6.3	1.7	0.88	0.50	0.20	0.10	0.05	0.03		
		Deep									0.33	3.8	94	251	253	102	4.8	0.90	0.33	0.15	0.10	0.08	0.03			
	Tech B	25 m/s					0.03	0.10	0.43	1.1	3.1	10.4	118	261	263	121	10.7	3.4	1.3	0.45	0.25	0.08	0.03			
		Moderate						0.03	0.13	0.38	1.6	6.8	114	258	260	117	7.6	2.3	1.0	0.55	0.28	0.20	0.10			
		Deep									0.55	4.8	113	258	259	116	5.8	1.1	0.5	0.35	0.08	0.05	0.05			

7.2.3 1 h ramps

Table 27 shows the results for 1 h ramps in GW. The differences between the scenarios are the same as discussed in Section 7.1.3, but here the scenarios with more installed GW of course show more extreme ramps. The tendency of the ramp distribution to be skewed to the right shows a higher number of events, for example, for 2 GW up-ramps than for 2 GW down-ramps. This is discussed further in Section 8.4. As with the 5 min and 15 min ramps, the Deep type lowers the likelihoods of large negative ramps (more than 2 GW) both in the 4.4 GW and 5.8 GW scenarios; however, the capability to lower the most extreme negative ramps is more pronounced in the 5.8 GW scenario.

Table 27. 1 h ramps: average number of days per year with at least one event more extreme than the limit.

			Negative Ramp (GW)												Positive Ramp (GW)											
			5.5	**5.0**	**4.5**	**4.0**	**3.5**	**3.0**	**2.5**	**2.0**	**1.5**	**1.0**	**0.5**	**0.3**	**0.3**	**0.5**	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**	**5.5**
0.9 GW													1.0	25	29	2.9										
2.3 GW											0.20	6.4	130	249	248	133	9.4	1.2	0.20							
3.0 GW	**Tech A**	**25 m/s**								0.10	1.6	23	193	281	280	193	27	3.7	0.60	0.13	0.05					
		Moderate								0.13	1.9	23	191	280	278	191	26	3.8	0.70	0.15	0.05					
		Deep								0.08	1.5	22	191	279	278	191	26	3.6	0.60	0.15	0.03					
	Tech B	**25 m/s**								0.10	1.7	24	196	283	283	196	26	3.5	0.53	0.13	0.05					
		Moderate								0.15	1.9	24	194	281	281	194	25	3.6	0.63	0.13	0.03					
		Deep								0.10	1.7	23	193	281	280	193	25	3.4	0.63	0.15	0.05					
4.4 GW	**Tech A**	**25 m/s**					0.03	0.23	0.90	3.8	16	84	257	313	311	256	91	20	6.0	2.0	0.55	0.28	0.13			
		Moderate					0.03	0.13	0.63	2.9	14	82	255	312	310	254	89	18	4.8	1.8	0.70	0.33	0.15			
		Deep					0.03	0.05	0.23	1.9	13	81	255	312	310	254	88	17	4.0	1.3	0.48	0.25	0.13			
	Tech B	**25 m/s**					0.03	0.13	0.80	5.0	20	96	261	315	313	260	98	22	5.8	1.7	0.38	0.23	0.13			
		Moderate					0.03	0.13	0.90	3.8	18	93	259	313	311	257	96	20	4.8	1.8	0.63	0.30	0.13			
		Deep					0.03	0.08	0.43	2.7	17	92	258	313	311	257	94	19	3.9	1.2	0.48	0.28	0.13			
5.8 GW	**Tech A**	**25 m/s**	0.03	0.03	0.08	0.58	1.4	2.8	6.0	15	52	160	291	328	327	291	165	58	19	8.4	4.2	2.4	0.90	0.33	0.15	0.08
		Moderate		0.03	0.05	0.23	0.65	1.6	4.2	13	49	158	289	327	326	289	162	56	17	6.6	3.1	1.6	1.0	0.45	0.23	0.13
		Deep				0.05	0.15	0.48	2.9	11	48	157	289	327	326	289	161	54	16	5.5	2.2	0.90	0.45	0.28	0.18	0.05
	Tech B	**25 m/s**	0.03	0.03	0.05	0.25	1.7	3.7	8.1	20	63	175	293	328	328	292	178	67	24	9.3	4.7	2.6	0.70	0.23	0.13	0.05
		Moderate		0.03	0.05	0.23	0.85	1.9	5.7	17	59	172	291	327	326	290	175	64	21	7.1	3.3	1.9	1.0	0.33	0.18	0.10
		Deep				0.05	0.28	1.0	4.2	15	58	171	291	326	326	290	174	63	19	5.7	2.2	1.1	0.65	0.35	0.20	0.13

7.3 Ramps in GW when daily max wind speed is low

The previous section has shown expected ramp event likelihoods when considering all the simulated days. This section shows the likelihoods when considering only days when the maximum daily wind speed (fleet-level mean, weighted by installed capacity) is below 20 m/s, thereby excluding in principle storm events which are considered separately in Section 8.

7.3.1 5 min ramps when daily max wind speed is low

Table 28 shows that for non-storm days, the different storm shutdown types show very similar 5 min ramp distributions; the results are not identical, because some storms last from one day to another, and, e.g., the ramps caused by the return from the storm may be marked on a day where the day's fleet-level maximum wind speed is below 20 m/s. Comparing to Table 25, it can be seen that the most extreme negative ramps (larger than 1.5 GW) do not happen on non-storm days in the 5.8 GW scenarios.

Table 28. 5 min ramps: average number of days per year with at least one event when the daily max fleet-level wind speed is below 20 m/s.

			Negative Ramp (GW)												Positive Ramp (GW)											
			5.5	5.0	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0	0.5	0.3	0.3	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5
0.9 GW															0.03											
2.3 GW														1.1	0.50											
3.0 GW	Tech A	25 m/s											0.15	2.0	2.8	0.08										
		Moderate											0.10	1.9	2.7	0.05										
		Deep											0.05	1.9	2.6											
	Tech B	25 m/s											0.23	2.5	2.7	0.18										
		Moderate											0.10	2.3	2.6	0.05										
		Deep											0.05	2.3	2.6											
4.4 GW	Tech A	25 m/s										0.13	0.80	7.9	8.9	0.90	0.08									
		Moderate											0.60	7.7	8.7	0.75										
		Deep											0.58	7.7	8.6	0.73										
	Tech B	25 m/s										0.13	1.10	10	10	1.1	0.10									
		Moderate											0.90	9.9	9.8	0.98										
		Deep											0.88	9.9	9.8	0.95										
5.8 GW	Tech A	25 m/s										0.05	2.5	22	24	2.0	0.05									
		Moderate											2.4	22	24	1.9										
		Deep											2.4	22	24	1.9										
	Tech B	25 m/s										0.08	3.0	29	31	2.8	0.08									
		Moderate										0.05	2.9	29	31	2.7										
		Deep										0.05	2.9	29	31	2.7										

7.3.2 15 min ramp when daily max wind speed is low

Like the 5 min ramps, also the 15 min ramps on non-storm days show similar behaviour for the different storm shutdown types, as seen in Table 29.

Table 29. 15 min ramps: average number of days per year with at least one event when the daily max fleet-level wind speed is below 20 m/s.

			Negative Ramp (GW)												Positive Ramp (GW)											
			5.5	5.0	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0	0.5	0.3	0.3	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5
0.9 GW														0.63	0.18	0.03										
2.3 GW													3.5	42	46	3.7										
3.0 GW	Tech A	25 m/s											8.5	88	91	9.5	0.03									
		Moderate											8.4	88	91	9.5	0.03									
		Deep											8.4	88	91	9.4	0.03									
	Tech B	25 m/s										0.03	9.6	92	91	9.4	0.03									
		Moderate										0.03	9.5	91	91	9.3	0.03									
		Deep										0.03	9.4	91	91	9.3	0.03									
4.4 GW	Tech A	25 m/s										0.85	31	177	180	34	0.95									
		Moderate										0.73	31	177	180	34	0.85									
		Deep										0.73	31	177	180	34	0.85									
	Tech B	25 m/s										1.0	39	188	189	38	1.1	0.03								
		Moderate										0.88	39	188	189	38	0.95	0.03								
		Deep										0.88	39	188	189	38	0.95	0.03								
5.8 GW	Tech A	25 m/s									0.28	3.3	87	237	240	94	3.6	0.25								
		Moderate									0.28	3.2	87	237	240	94	3.5	0.25								
		Deep									0.28	3.2	87	237	240	94	3.5	0.25								
	Tech B	25 m/s									0.45	4.2	106	244	245	108	4.6	0.30								
		Moderate									0.45	4.1	106	244	245	108	4.5	0.30								
		Deep									0.45	4.1	106	244	245	108	4.5	0.30								

7.3.3 1 h ramp when daily max wind speed is low

Table 30 shows the 1 h ramps for days when the maximum wind speed is below 20 m/s. An example large ramp event is visualised in Figure 25. The results are identical for all shutdown types. Comparing to Table 27, the most extreme negative ramps (larger than 4.5 GW) in the 5.8 GW scenarios do not happen on non-storm days.

Table 30. 1 h ramps: average number of days per year with at least one event when the daily max fleet-level wind speed is below 20 m/s.

			Negative Ramp (GW)												Positive Ramp (GW)											
			5.5	**5.0**	**4.5**	**4.0**	**3.5**	**3.0**	**2.5**	**2.0**	**1.5**	**1.0**	**0.5**	**0.3**	**0.3**	**0.5**	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**	**5.5**
0.9 GW													0.48	21	25	1.5										
2.3 GW											0.20	5.4	122	237	236	125	7.6	0.63	0.05							
3.0 GW	**Tech A**	**25 m/s**								0.05	1.2	19	181	266	264	180	22	2.4	0.18							
		Moderate								0.05	1.2	19	181	266	264	180	22	2.4	0.18							
		Deep								0.05	1.2	19	181	266	264	180	22	2.4	0.18							
	Tech B	**25 m/s**								0.08	1.2	20	183	267	266	183	21	2.3	0.15							
		Moderate								0.08	1.2	20	183	267	266	183	21	2.3	0.15							
		Deep								0.08	1.2	20	183	267	266	183	21	2.3	0.15							
4.4 GW	**Tech A**	**25 m/s**						0.03	0.08	1.4	11	75	243	296	294	241	81	15	2.8	0.65	0.13	0.05				
		Moderate						0.03	0.08	1.4	11	75	243	296	294	241	81	15	2.8	0.65	0.13	0.05				
		Deep						0.03	0.08	1.4	11	75	243	296	294	241	81	15	2.8	0.65	0.13	0.05				
	Tech B	**25 m/s**						0.03	0.23	2.1	14	85	246	297	294	244	87	16	2.6	0.55	0.10	0.05				
		Moderate						0.03	0.23	2.1	14	85	246	297	294	244	87	16	2.6	0.55	0.10	0.05				
		Deep						0.03	0.23	2.1	14	85	245	297	294	244	87	16	2.6	0.55	0.10	0.05				
5.8 GW	**Tech A**	**25 m/s**				0.05	0.08	0.28	2.3	9.6	43	148	274	309	308	273	151	49	13	3.9	1.2	0.28	0.08	0.05		
		Moderate				0.05	0.08	0.28	2.3	9.6	43	148	274	309	308	273	151	49	13	3.9	1.2	0.28	0.08	0.05		
		Deep				0.05	0.08	0.28	2.3	9.6	43	148	274	309	308	273	151	49	13	3.9	1.2	0.28	0.08	0.05		
	Tech B	**25 m/s**				0.05	0.13	0.63	3.4	13	53	161	275	308	307	274	163	57	17	4.1	1.1	0.28	0.10	0.03		
		Moderate				0.05	0.13	0.63	3.4	13	53	161	275	308	307	274	163	57	16	4.1	1.1	0.28	0.10	0.03		
		Deep				0.05	0.13	0.63	3.4	13	53	161	275	308	307	274	163	57	16	4.1	1.1	0.28	0.10	0.03		

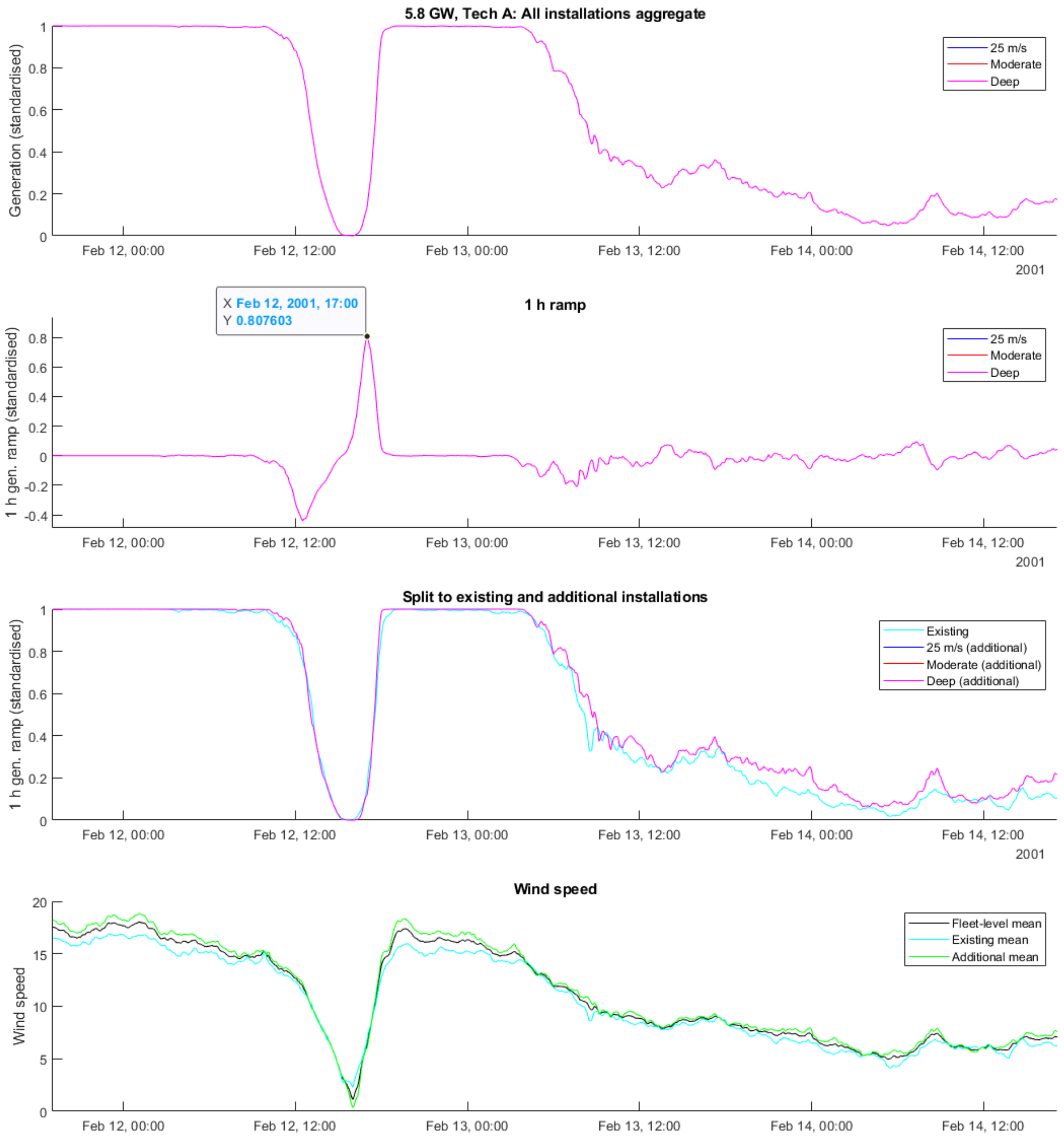

Figure 25. The most extreme up-ramp event for the 5.8 GW Tech A scenario when considering days with max wind speed below 20 m/s. As wind speeds are < 20 m/s, all storm shutdown types show the same generation time series. "Existing" refers to the 2.3 GW of installations and "additional" to the 3.5 GW of additional installation to reach 5.8 GW.

7.4 Conclusions on ramps

When considering the standardized generation, ramps (including ramps following storm events) are found to, as expected, to be reduced towards the 5.8 GW of installations. This is caused by geographical smoothening. It is found that 5 min ramps are reduced more than 1-hour ramps.

However, when expressed in GW, ramps are, as expected, increasing significantly towards the future. In the 4.4 GW scenarios, ramps of more than 2 GW in 1 hour are expected to occur on 2-6 days a year (considering both up- and down-ramps). In the 5.8 GW scenarios, this increases to 11-24 days a year, depending on the technology considered. Even 4 GW ramps and more for up-ramps in 1 hour are seen in the 40-year simulation for the 5.8 GW scenarios. It seems that extreme up-ramps are more likely than similar size down-ramps (this is discussed further in Section 8.4) following the behaviour during storms. Results show that Tech B results in a slightly larger frequency of the higher ramps compared to Tech A, while the high wind speed technologies have a significant mitigating effect on the occurrence of large ramps.

When focusing on non-storm days (maximum wind speeds lower than 20 m/s), it is found that the largest negative ramps do not seem to occur on non-storm days. In the 4.4 GW scenarios, ramps of more than 2 GW in 1 hour are expected to occur on 2-6 days a year (considering both up- and down-ramps). In the 5.8 GW scenarios, this increases to 11-24 days a year, depending on the technology considered. It is to be noted that 1-hour down-ramps larger than 4.5 GW, observed a few times during the whole 40-year simulations for the 5.8 GW scenarios, are not observed on non-storm days. The most extreme 1-hour up-ramps (5.0 GW or higher) are also not observed on non-storm days. Note that the different storm shutdown types do not show any significant differences in ramps for non-storm days, as expected. However, a large up-ramp event related to return from a storm may be recorded on a low wind speed day if it happens after midnight following a storm day.

The most extreme ramps observed during the simulated 40 years for non-storm days for the 5.8 GW scenarios are as follows. For 5 min ramps, down-ramps larger than 1.0 GW are expected on less than 0.1 days/year, and up-ramps larger than 1.0 GW on less than 0.1 days/year for the 25 m/s direct cut-off and not at all for the Moderate and Deep technologies. For 15 min ramps, down-ramps larger then 1.5 GW are expected on less than 0.5 days/year, and up-ramps larger than 1.5 GW on approximately 0.3 days/year. For 1 h ramps, down-ramps larger then 4.0 GW are expected on less than 0.1 days/year, and up-ramps larger than 4.5 GW on less than 0.1 days/year.

It is important to note that the likelihoods of the most extreme ramp events may be slightly underestimated, based on the comparison between measured and simulated data in Section 0.

8. Statistical analysis of storm events

This chapter presents statistics of storm events in the simulated 40 years of data. Both the likelihoods of fleet-wide shutdowns and ramping during high wind speed days (maximum wind speed above 20 m/s) are reported. All results are given based on the simulated 5 min resolution data.

8.1 Simulated 40 years of wind speeds

Simulated fleet-level wind speeds for the 5.8 GW Tech B scenario can be seen in Figure 26 based on a 5 min resolution. The highest fleet-level wind speed reaches approximately 38 m/s while highest plant-level wind speeds are even higher. It can be observed that high wind speeds occur throughout the 40 years and most extreme peaks occurred in the 80s and 90s. It has to be noted that the Tech B scenario shows slightly higher fleet-level wind speeds than Tech A due to higher hub heights. Compared to the 2020 report, the highest peaks appear on the same dates but the exact peak wind speeds are slightly different (some lower and some higher).

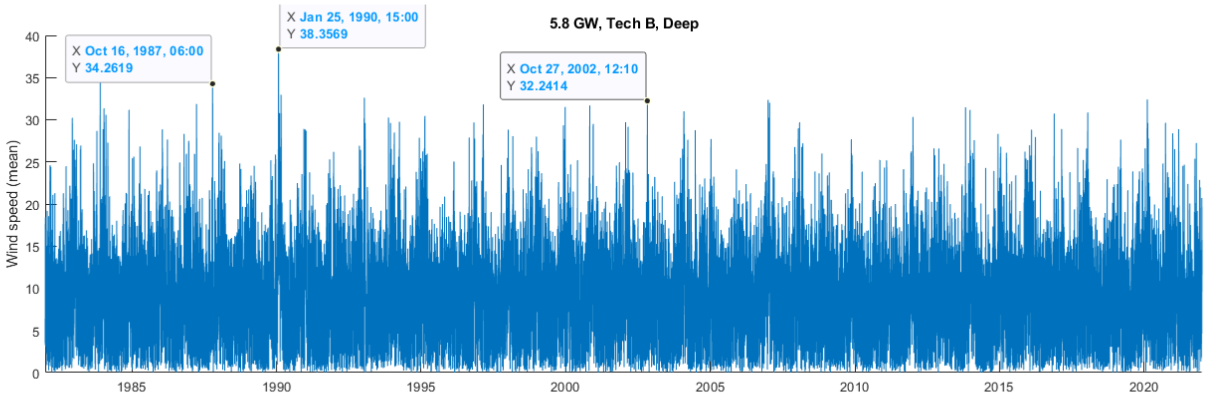

Figure 26. Fleet-level mean wind speeds (weighted by OWPP installed capacity) in the 5.8 GW Tech B scenario (5 min resolution), with some example high peaks highlighted.

8.2 Generation during storms

Example time series around the 1990 extreme high wind speed event can be seen in Figure 27. With such high wind speeds, the entire fleet (5.8 GW) is in shutdown for some hours with all the scenarios considered. In this specific example, the Deep type shows lower ramping (both 5 min and 1 h) than the 25 m/s cut-off. However, the Moderate type shows higher ramping than the 25 m/s cut-off, even though the cut-off happens at higher wind speeds. This is explained as in this example, the wind speed variation is slightly faster around the Moderate type cut-off wind speeds, causing higher ramps than with the 25 m/s cut-off. This shows that the storm shutdown types should be compared based on statistics over a longer time series rather than on individual cases.

Figure 28 shows that even with the Deep shutdown type, the 5.8 GW Tech B scenario is expected to sometimes experience a total fleet-wide shut-down. Figure 29 shows that the storm shut down type has a limited impact in reducing the number of occurrences where the entire fleet experiences a total shut-down, although the Deep type prevents the complete fleet-level shutdown in two years for Tech A.

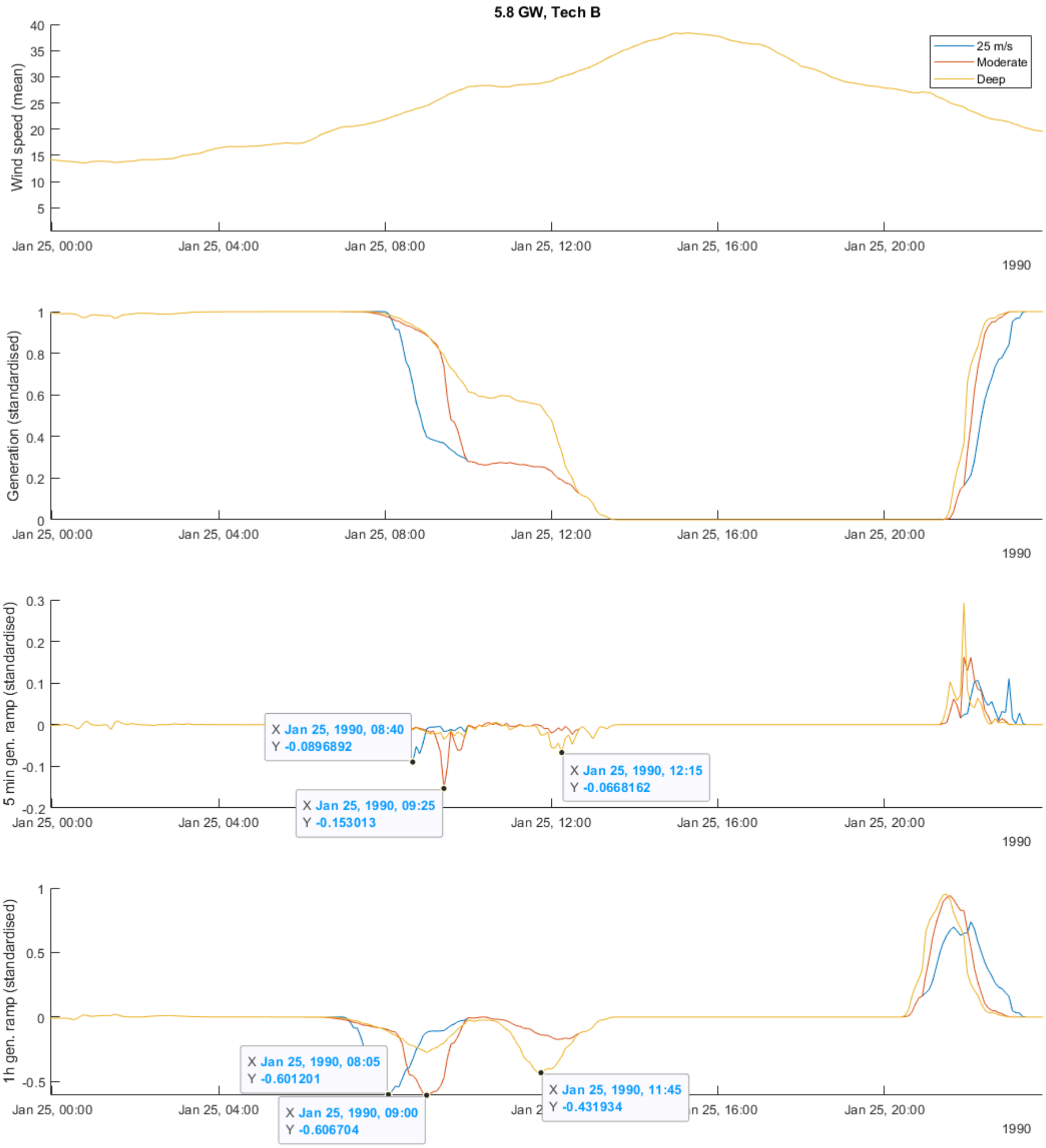

Figure 27. Simulated time series for an extreme storm case for the 5.8 GW Tech B scenario.

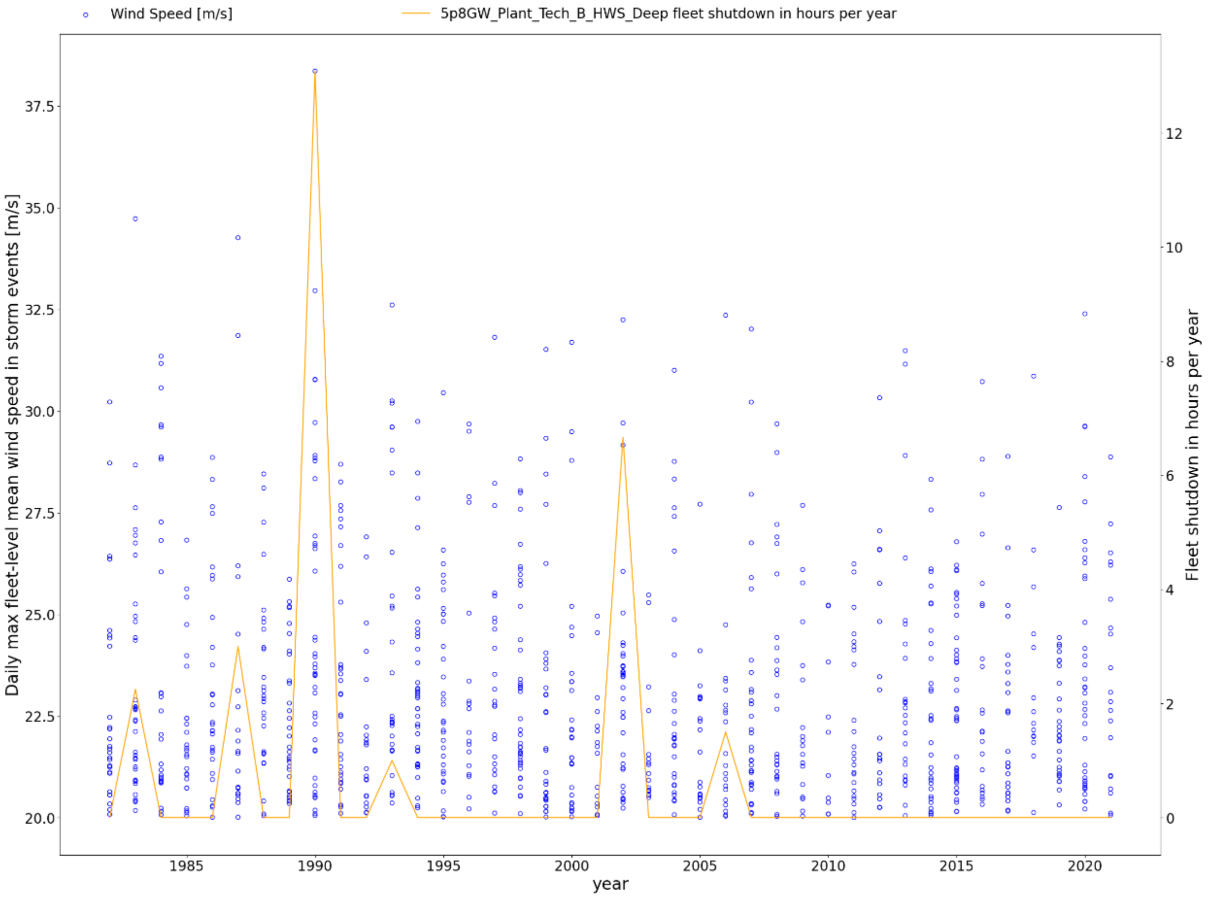

Figure 28. Number of hours when the entire fleet is in shutdown (aggregate generation zero) per year in the 5.8 GW Tech B Deep scenario (right), and daily max wind speeds above 20 m/s (left) for each year.

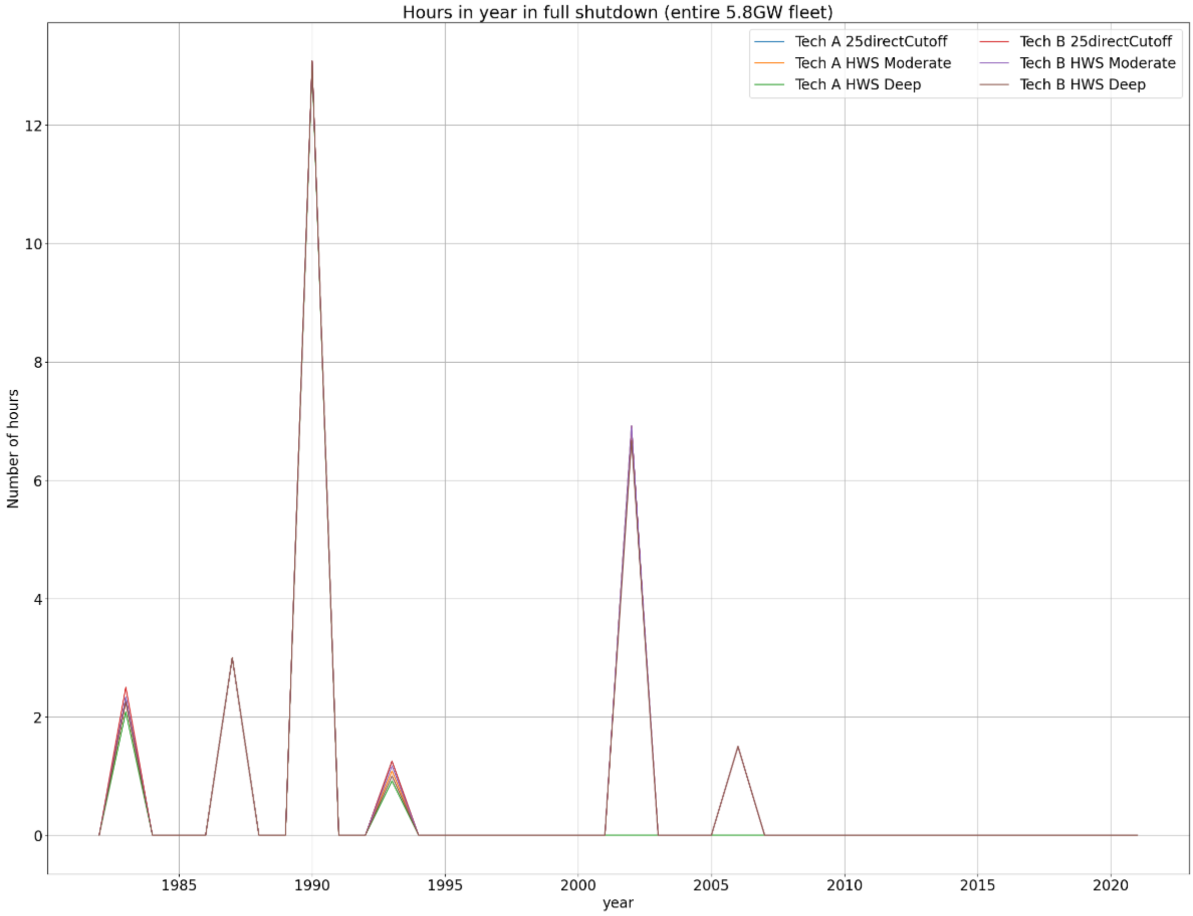

Figure 29. Number of hours when the entire fleet is in shut-down (aggregate generation zero) per year for the 5.8 GW scenarios[3].

8.3 Ramps in GW during high wind speed days

This section describes the ramps during high wind days (maximum daily fleet-level wind speed above 20 m/s) and the average number of days per year with at least one ramp event more extreme than a given value expressed in GW.

8.3.1 5 min ramps during high wind speed days

Table 31 shows the 5 min ramps in GW for high wind speed days**.** Comparing to Table 25, for the 25 m/s cut-off and Moderate types, the most extreme negative ramps occur on high wind days for both the 4.4 GW and 5.8 GW scenarios. However, for the Deep type, the largest negative ramps (above 0.5 GW) happen both on storm and non-storm days, highlighting the Deep type's capability to reduce negative 5 min ramps during storms to a level occurring even on non-storm days (i.e., the largest negative ramp for the 4.4 GW or 5.8 GW Deep type in Table 31 is lower than or the same as in Table 28). Thus, any smoother storm shutdown technology could not further reduce the most extreme down-ramps (when considering all days), because they happen on non-storm days anyway.

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[3] A fleet-level full shutdown was observed in 2022 (2.3 GW installation case). However, as weather data in CorRES is available only until 2021, it was not possible to validate the simulations to this event.

For all shutdown types, the most extreme positive ramps happen on storm days. This is caused by the different behaviour during storm shutdown compared to the restart after the shutdown, and is discussed further in Section 8.4 The observed asymmetry in Table 31 (more positive than negative very high ramps) is a consequence of this effect. Note that Tech A and Tech B show similar results in Table 31. However, the high ramp likelihoods are overall slightly larger for Tech B. Tech B shows slightly higher ramps during high wind speed days, as it has a higher hub height compared to Tech A (see Table 1 and Table 2) and therefore also the likelihood of going beyond the cut-off wind speed is higher.

Table 31. 5 min ramps: average number of days per year with at least one event more extreme than the limit for days with max fleet-level wind speed above 20 m/s.

			Negative Ramp (GW)												Positive Ramp (GW)											
			5.5	5.0	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0	0.5	0.3	0.3	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5
0.9 GW															0.03											
2.3 GW														0.13	0.38	0.08										
3.0 GW	Tech A	25 m/s										0.03	0.30	1.2	1.7	0.30	0.05									
		Moderate											0.10	1.5	1.4	0.28	0.03									
		Deep												0.33	0.78	0.25	0.03									
	Tech B	25 m/s											0.23	1.3	1.6	0.25	0.05									
		Moderate											0.28	1.5	1.7	0.30	0.05									
		Deep											0.03	0.38	0.85	0.28	0.03									
4.4 GW	Tech A	25 m/s										0.18	2.2	5.4	5.1	2.0	0.38	0.03								
		Moderate										0.08	1.1	2.9	3.1	1.3	0.20	0.03								
		Deep											0.10	0.83	1.6	0.45	0.05	0.03								
	Tech B	25 m/s										0.28	2.4	6.4	6.2	2.0	0.25	0.03								
		Moderate										0.10	1.6	3.4	3.5	1.7	0.33	0.03								
		Deep											0.13	0.95	1.8	0.55	0.08									
5.8 GW	Tech A	25 m/s									0.13	0.78	4.5	8.1	8.1	4.0	0.68	0.03								
		Moderate										0.38	2.3	4.2	4.6	2.4	0.58	0.15	0.05							
		Deep											0.30	2.5	3.1	0.85	0.23	0.08	0.03							
	Tech B	25 m/s								0.03	0.10	0.85	5.6	9.7	9.9	5.3	0.65	0.05								
		Moderate									0.05	0.35	2.5	5.0	5.5	3.0	0.70	0.23	0.03							
		Deep											0.58	2.9	3.6	1.2	0.38	0.10	0.05							

8.3.2 15 min ramps during high wind speed days

Table 32 shows the 15 min ramps in GW for the high wind speed days**.** Comparing to Table 26, most days with extreme negative 15 min ramps occur on high wind days for the 25 m/s cut-off and Moderate types in the 4.4 GW and 5.8 GW scenarios. However, for the Deep type, the most extreme negative ramps (more than 1.5 GW in the 5.8 GW scenarios) occur both on storm and non-storm days. This shows that the Deep type has managed to reduce the 15 min ramps on storm days to a level which can occur even on non-storm days (i.e., the largest negative ramp for the 4.4 GW or 5.8 GW Deep type in Table 32 is lower than or the same as in Table 29). Thus, any smoother storm shutdown technology could not further reduce the most extreme down-ramps (when considering all days), because they happen on non-storm days anyway.

The very large positive ramps (above 3.0 GW) are slightly reduced for the Deep type compared to the 25 m/s cut-off in the 5.8 GW scenarios. However, the most extreme up-ramps have very similar likelihood for all the types; this is discussed more in Section 8.4. Tech A and Tech B show similar results in Table 32.

Table 32. 15 min ramps: average number of days per year with at least one event more extreme than the limit for days with max fleet-level wind speed above 20 m/s.

			Negative Ramp (GW)												Positive Ramp (GW)											
			5.5	5.0	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0	0.5	0.3	0.3	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5
0.9 GW														0.30	0.98	0.20										
2.3 GW													0.45	3.5	4.4	1.0	0.15	0.05	0.03							
3.0 GW	Tech A	25 m/s										0.10	2.9	9.1	9.2	3.7	0.33	0.10	0.03	0.03						
		Moderate										0.10	2.4	7.0	7.4	3.2	0.33	0.10	0.05							
		Deep										0.03	1.2	6.0	6.4	2.0	0.25	0.08	0.03							
	Tech B	25 m/s										0.10	3.0	10	10	3.6	0.30	0.10	0.03							
		Moderate										0.08	3.1	7.9	8.2	3.3	0.33	0.10	0.05	0.03						
		Deep										0.03	1.4	6.4	6.7	2.0	0.30	0.10	0.05							
4.4 GW	Tech A	25 m/s								0.03	0.50	2.2	7.4	13	14	8.0	2.5	0.73	0.23	0.10	0.05	0.03				
		Moderate								0.05	0.28	1.2	4.6	11	11	5.6	1.6	0.55	0.25	0.13	0.03	0.03				
		Deep										0.10	3.1	10	10	4.1	0.60	0.28	0.10	0.03						
	Tech B	25 m/s								0.03	0.55	2.7	8.9	14	15	8.9	2.7	0.60	0.20	0.08	0.08					
		Moderate								0.05	0.38	1.6	5.6	11	11	5.8	1.7	0.80	0.33	0.13	0.05	0.03				
		Deep										0.23	3.7	10	10	4.0	0.70	0.33	0.25	0.05						
5.8 GW	Tech A	25 m/s						0.08	0.33	1.00	2.3	5.0	11	16	16	12	4.9	2.5	1.1	0.50	0.23	0.10	0.03			
		Moderate							0.05	0.33	1.1	2.4	7.7	14	14	8.8	2.8	1.5	0.88	0.50	0.20	0.10	0.05	0.03		
		Deep									0.05	0.53	7.0	14	14	7.5	1.3	0.65	0.33	0.15	0.10	0.08	0.03			
	Tech B	25 m/s					0.03	0.10	0.43	1.1	2.6	6.3	13	17	18	13	6.2	3.1	1.3	0.45	0.25	0.08	0.03			
		Moderate						0.03	0.13	0.38	1.2	2.7	8.7	14	15	9.4	3.2	2.0	1.0	0.55	0.28	0.20	0.10			
		Deep									0.10	0.73	7.4	14	14	7.8	1.4	0.83	0.53	0.35	0.08	0.05	0.05			

8.3.3 1 h ramps during high wind speed days

Table 33 shows the 1 h ramps in GW for the high wind speed days. Comparing to Table 27, for the 4.4 GW scenarios, the Deep type shows reduced likelihoods for large negative ramps (larger than 2.5 GW) compared to the 25 m/s cut-off. However, the most extreme negative ramps (larger than 3.5 GW) are the same for all the shutdown types. For the 5.8 GW case, the Deep type can reduce also the most extreme negative ramps (larger than 3.5 GW) significantly. The positive ramps are very high for all types, reaching higher than 5.0 GW for 1 or 2 days in 10 years; this is discussed further in Section 8.4.

Table 33. 1 h ramps: average number of days per year with at least one event more extreme than the limit for days with max fleet-level wind speed above 20 m/s.

			Negative Ramp (GW)												Positive Ramp (GW)											
			5.5	5.0	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0	0.5	0.3	0.3	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5
0.9 GW													0.48	3.2	4.4	1.4										
2.3 GW												0.98	7.7	12	12	7.7	1.8	0.53	0.15							
3.0 GW	Tech A	25 m/s								0.05	0.48	3.4	12	15	15	12	4.3	1.3	0.43	0.13	0.05					
		Moderate								0.08	0.70	3.3	11	14	14	11	4.2	1.3	0.53	0.15	0.05					
		Deep								0.03	0.38	2.6	10	14	14	10	3.3	1.2	0.43	0.15	0.03					
	Tech B	25 m/s								0.03	0.55	3.2	13	16	16	13	4.1	1.2	0.38	0.13	0.05					
		Moderate								0.08	0.68	3.5	11	14	14	11	4.0	1.3	0.48	0.13	0.03					
		Deep								0.03	0.53	2.7	10	14	14	10	3.3	1.1	0.48	0.15	0.05					
4.4 GW	Tech A	25 m/s					0.03	0.20	0.83	2.4	4.8	8.9	15	17	17	15	10	5.4	3.2	1.3	0.43	0.23	0.13			
		Moderate					0.03	0.10	0.55	1.5	3.0	6.7	13	15	16	14	8.3	3.9	2.0	1.1	0.58	0.28	0.15			
		Deep					0.03	0.03	0.15	0.48	2.0	5.8	13	15	16	13	7.4	2.6	1.2	0.63	0.35	0.20	0.13			
	Tech B	25 m/s					0.03	0.10	0.58	2.9	5.3	10	15	18	19	16	11	5.7	3.3	1.1	0.28	0.18	0.13			
		Moderate					0.03	0.10	0.68	1.7	3.5	7.3	13	16	17	14	8.4	4.0	2.3	1.3	0.53	0.25	0.13			
		Deep					0.03	0.05	0.20	0.60	2.1	6.2	13	16	17	13	7.1	2.7	1.3	0.60	0.38	0.23	0.13			
5.8 GW	Tech A	25 m/s	0.03	0.03	0.08	0.53	1.4	2.5	3.8	5.6	8.4	12	17	19	19	17	13	9.1	6.2	4.5	3.0	2.1	0.83	0.28	0.15	0.08
		Moderate		0.03	0.05	0.18	0.58	1.3	2.0	3.1	5.7	9.9	15	18	18	16	11	6.6	4.0	2.7	1.9	1.3	0.88	0.40	0.23	0.13
		Deep					0.08	0.20	0.65	1.7	4.6	9.6	15	18	18	16	10	5.4	2.7	1.5	1.0	0.63	0.38	0.23	0.18	0.05
	Tech B	25 m/s	0.03	0.03	0.05	0.20	1.6	3.1	4.7	6.6	9.6	14	18	20	20	18	14	10	7.1	5.2	3.6	2.3	0.60	0.20	0.13	0.05
		Moderate		0.03	0.05	0.18	0.73	1.3	2.3	3.7	6.3	11	16	19	19	16	11	7.2	4.4	2.9	2.2	1.6	0.90	0.30	0.18	0.10
		Deep					0.15	0.33	0.80	2.2	4.8	9.9	16	19	19	16	10	5.6	2.9	1.5	1.1	0.78	0.55	0.33	0.20	0.13

8.4 On the large up-ramps

From Table 31, Table 32 and Table 33, it can be seen that up-ramps are more likely than down-ramps of the same magnitude for high wind speed days. An example of this is shown in Figure 27, where all the shutdown types experience a very fast up-ramp after the storm. For Moderate and Deep types, this is impacted by the storm shutdown type only affecting the shutdown and not the restart operation during storm in terms of how fast the generation ramps when wind speed changes: looking at Figure 4, it can be seen that the Deep type restart happens on higher wind speed than the 25 m/s cut-off type, but the slope of the return-from-shutdown curve is the same. This behaviour was highlighted also in the 2020 report.

8.5 Conclusions on storm events

It is possible to lose the full 5.8 GW of installed capacity in all studied cases due to an extreme storm event. The number of years where this occurs is 4-6 out of the simulated 40 years for the 5.8 GW scenarios, depending on the technology.

Storm shutdown type impacts the most extreme fast ramps by slowing down the down-ramps during storms. 5 and 15 min extreme down ramps are reduced significantly when comparing the Deep to the 25 m/s cut-off type. For example, for 15 min ramps in the 5.8 GW scenarios, negative 2 GW down-ramp is seen in the simulations around 1 day per year for the 25 m/s cut-off type, but such event was not seen for the Deep type.

For 1-hour ramps in the 4.4 GW scenarios on high wind speed days, a negative ramp of more than 2 GW is expected to happen on a few days over a year with the 25 m/s cut-off type. For similar scenarios with the Deep storm shutdown type, such event is expected on less than one day a year. For the 5.8 GW case, the Deep type can reduce also the very large negative 1-hour ramps (larger than 3.5 GW) significantly compared to 25 m/s cut-off: they are reduced from around 1 day per year to around 1 day in 10 years. Overall, the Deep type can lower all the studied ramps (5 min, 15 min, 1 h) to a level seen even on non-storm days.

The most extreme ramps observed during the simulated 40 years for high wind speed days for the 25 m/s direct cut-off and Deep type in the 5.8 GW Tech B scenario (to compare the most distinct storm shutdown types in the scenario with overall largest ramps) are as follows. For 5 min down-ramps, larger than 2.0 GW ramps are expected on less than 0.1 days/year for the 25 m/s cut off, whereas for the Deep type larger than 1.0 GW ramps are not seen in the simulated data. For 5 min up-ramps, larger than 1.5 GW ramps are expected on less than 0.1 days/year for the 25 m/s cut-off and 2.0 GW ramps are not seen in the simulated data, whereas for the Deep type larger than 2.0 GW ramps are expected on less than 0.1 days/year. For 15 min down-ramps, larger than 3.5 GW ramps are expected on less than 0.1 days/year for the 25 m/s cut-off, whereas for the Deep type larger than 2.0 GW down-ramps are not seen in the simulated data. For 15 min up-ramps, larger than 4.0 GW ramps are expected on less than 0.1 days/year for both storm shutdown types. For 1 h down-ramps, larger than 5.5 GW ramps are expected on less than 0.1 days/year for the 25 m/s cut-off, whereas for the Deep type larger than 4.0 GW ramps are not seen in the simulated data. For 1 h up-ramps, larger than 5.5 GW ramps are expected on around 0.1 days/year for both storm shutdown types, with the Deep type showing slightly more large up-ramp events.

Highest 1-hour up-ramps are similar for all studied storm shutdown types. A contributor to this is that the storm shut-down slows only the shut-down and not the restart part of the power curve. The same conclusion is made in the 2020 report.

9. Statistical analysis of forecast errors

This chapter analyses the simulated forecast errors for the scenarios (also including periods with storm or extreme ramp events). The forecast errors are calculated as: $e_t = p_{t,actual} - p_{t,forecasted}$. Thus, a negative forecast error means that the forecasted generation is larger than actual generation. All forecast errors are analysed on 15 min resolution.

The first section compares the scenarios in standardized generation, as the impact of geographical smoothening is easier to see when all data are standardized. The further sections show results in GW

9.1 Forecast errors in standardized generation

9.1.1 Day-ahead forecasts

Table 34 shows the day-ahead forecast error statistics for the different scenarios. The forecast error SD decreases from the 0.9 GW scenario towards the 5.8 GW scenarios. This decrease is due to increased geographical distribution (on aggregate, it is easier to forecast a larger than a smaller region). Tech A and Tech B scenarios show similar statistics.

Table 34. Day-head forecast error statistics.

									Compared to 0.9 GW
			mean	**SD**	**Prct 0.001**	**Prct 0.01**	**Prct 99.99**	**Prct 99.999**	**SD**
0.9 GW			-0.003	0.128	-0.818	-0.669	0.704	0.900	100%
2.3 GW			-0.003	0.126	-0.735	-0.650	0.656	0.836	99%
3.0 GW	**Tech A**	**25 m/s**	-0.002	0.121	-0.719	-0.639	0.622	0.714	95%
		Moderate	-0.002	0.121	-0.738	-0.641	0.624	0.729	95%
		Deep	-0.002	0.121	-0.740	-0.640	0.624	0.737	94%
	Tech B	**25 m/s**	-0.002	0.121	-0.719	-0.643	0.618	0.706	95%
		Moderate	-0.002	0.121	-0.719	-0.644	0.620	0.709	95%
		Deep	-0.002	0.121	-0.739	-0.644	0.622	0.728	95%
4.4 GW	**Tech A**	**25 m/s**	-0.002	0.114	-0.673	-0.601	0.648	0.810	89%
		Moderate	-0.003	0.113	-0.676	-0.602	0.646	0.823	89%
		Deep	-0.003	0.113	-0.672	-0.594	0.637	0.823	88%
	Tech B	**25 m/s**	-0.001	0.116	-0.674	-0.602	0.661	0.787	91%
		Moderate	-0.002	0.115	-0.674	-0.604	0.662	0.799	90%
		Deep	-0.002	0.115	-0.674	-0.601	0.660	0.800	90%
5.8 GW	**Tech A**	**25 m/s**	-0.003	0.113	-0.731	-0.608	0.647	0.745	88%
		Moderate	-0.003	0.112	-0.763	-0.639	0.636	0.763	87%
		Deep	-0.003	0.111	-0.725	-0.589	0.584	0.757	87%
	Tech B	**25 m/s**	-0.002	0.116	-0.711	-0.608	0.636	0.701	91%
		Moderate	-0.002	0.115	-0.741	-0.644	0.640	0.747	90%
		Deep	-0.002	0.114	-0.733	-0.605	0.608	0.766	89%

9.1.2 Intraday forecasts

Table 35 shows the intraday forecast error statistics. The forecast error SD decreases from the 0.9 GW scenario towards the 5.8 GW scenarios, with the Deep type showing slightly lower uncertainty then the 25 m/s cut-off type in the 5.8 GW scenarios. This is discussed further in Section 9.3. Tech A and Tech B scenarios show similar statistics. The forecast error SDs are somewhat lower than for day-ahead (see Table 34).

Table 35. Intraday forecast error statistics.

									Compared 0.9 GW
			mean	**SD**	**Prct 0.001**	**Prct 0.01**	**Prct 99.99**	**Prct 99.999**	**SD**
0.9 GW			-0.002	0.100	-0.724	-0.550	0.542	0.647	100%
2.3 GW			-0.002	0.099	-0.655	-0.555	0.518	0.601	99%
3.0 GW	**Tech A**	**25 m/s**	-0.002	0.094	-0.636	-0.528	0.514	0.605	95%
		Moderate	-0.002	0.094	-0.640	-0.532	0.516	0.636	95%
		Deep	-0.002	0.094	-0.641	-0.529	0.519	0.627	94%
	Tech B	**25 m/s**	-0.001	0.095	-0.642	-0.533	0.510	0.598	95%
		Moderate	-0.001	0.094	-0.642	-0.535	0.513	0.620	95%
		Deep	-0.001	0.094	-0.651	-0.534	0.515	0.640	95%
4.4 GW	**Tech A**	**25 m/s**	-0.002	0.090	-0.614	-0.510	0.512	0.571	90%
		Moderate	-0.002	0.089	-0.579	-0.489	0.499	0.586	89%
		Deep	-0.002	0.089	-0.563	-0.481	0.480	0.563	89%
	Tech B	**25 m/s**	-0.001	0.091	-0.605	-0.518	0.498	0.585	91%
		Moderate	-0.001	0.091	-0.625	-0.502	0.516	0.608	91%
		Deep	-0.001	0.090	-0.586	-0.492	0.490	0.600	90%
5.8 GW	**Tech A**	**25 m/s**	-0.001	0.089	-0.654	-0.514	0.559	0.709	89%
		Moderate	-0.001	0.088	-0.710	-0.512	0.512	0.645	88%
		Deep	-0.001	0.088	-0.566	-0.481	0.484	0.592	88%
	Tech B	**25 m/s**	-0.001	0.092	-0.656	-0.537	0.572	0.667	92%
		Moderate	-0.001	0.091	-0.692	-0.520	0.526	0.633	91%
		Deep	-0.001	0.090	-0.573	-0.490	0.495	0.626	90%

9.1.3 Latest forecasts

Table 36 shows the Last forecast error statistics for the scenarios. The forecast error SD decreases from the 0.9 GW scenario towards the 5.8 GW scenarios. Overall, the Deep storm shut-down type shows very slightly reduced forecast uncertainty compared to 25 m/s cut-off type. This is discussed further in Section 9.3. Tech A and Tech B scenarios show similar statistics. The forecast error SDs are somewhat lower than for Intraday (see Table 35).

Table 36. Last forecast error statistics.

									Compared to 0.9 GW
			mean	**SD**	**Prct 0.001**	**Prct 0.01**	**Prct 99.99**	**Prct 99.999**	**SD**
0.9 GW			-0.001	0.072	-0.690	-0.466	0.451	0.696	100%
2.3 GW			-0.001	0.071	-0.545	-0.449	0.428	0.545	99%
3.0 GW	**Tech A**	**25 m/s**	0.000	0.069	-0.546	-0.416	0.424	0.518	95%
		Moderate	0.000	0.068	-0.546	-0.421	0.426	0.518	95%
		Deep	0.000	0.068	-0.546	-0.420	0.423	0.518	95%
	Tech B	**25 m/s**	0.000	0.069	-0.534	-0.416	0.423	0.513	95%
		Moderate	0.000	0.069	-0.534	-0.420	0.423	0.517	95%
		Deep	0.000	0.068	-0.539	-0.421	0.422	0.513	95%
4.4 GW	**Tech A**	**25 m/s**	0.000	0.065	-0.546	-0.405	0.427	0.563	90%
		Moderate	0.000	0.064	-0.630	-0.404	0.427	0.601	89%
		Deep	0.000	0.064	-0.460	-0.367	0.387	0.496	88%
	Tech B	**25 m/s**	0.000	0.066	-0.500	-0.406	0.410	0.530	91%
		Moderate	0.000	0.065	-0.656	-0.390	0.431	0.619	91%
		Deep	0.000	0.065	-0.455	-0.375	0.396	0.530	90%
5.8 GW	**Tech A**	**25 m/s**	0.000	0.064	-0.600	-0.464	0.409	0.533	89%
		Moderate	0.000	0.064	-0.608	-0.448	0.382	0.515	88%
		Deep	0.000	0.063	-0.530	-0.401	0.372	0.610	87%
	Tech B	**25 m/s**	0.000	0.066	-0.598	-0.468	0.435	0.530	92%
		Moderate	0.000	0.065	-0.605	-0.462	0.394	0.502	90%
		Deep	0.000	0.065	-0.578	-0.414	0.385	0.507	90%

9.2 Forecast errors in GW

9.2.1 Day-ahead forecasts

Table 37 shows the average number of days per year with at least one day-ahead forecast error more extreme than the given GW limit. Tech A and Tech B scenarios show similar statistics. The differences between the different storm shutdown types are small.

Table 37. Day-ahead forecast errors: average number of days per year with at least one event.

			Negative forecast error (GW)												Positive forecast error (GW)											
			5.5	5.0	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0	0.5	0.3	0.3	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5
0.9 GW													3.4	45.1	40.4	3.4										
2.3 GW											0.8	19.3	110.0	181.5	181.2	108.1	17.8	0.8	0.1							
3.0 GW	Tech A	25 m/s								0.5	6.6	40.4	142.3	209.0	209.4	141.1	39.9	6.1	0.3	0.0						
		Moderate								0.5	6.7	40.4	141.3	207.6	207.9	139.6	39.7	6.0	0.3	0.0						
		Deep							0.0	0.5	6.6	40.1	140.8	207.1	207.4	139.0	39.4	5.9	0.4	0.0						
	Tech B	25 m/s								0.6	6.7	40.5	142.9	209.8	211.7	142.7	39.7	5.9	0.4	0.0						
		Moderate								0.6	6.8	40.6	141.9	207.9	209.1	140.8	39.6	5.9	0.4	0.0						
		Deep							0.0	0.6	6.7	40.4	141.1	207.2	208.8	140.1	39.3	5.9	0.4	0.0						
4.4 GW	Tech A	25 m/s						0.1	1.1	6.8	28.5	83.6	186.5	241.9	242.3	187.3	83.5	28.7	7.6	1.4	0.3	0.1				
		Moderate						0.1	1.1	6.6	27.9	82.4	184.4	240.3	240.7	185.1	81.0	27.3	7.0	1.3	0.3	0.1	0.0			
		Deep						0.1	1.0	6.3	27.4	81.7	184.0	239.9	240.4	184.6	80.2	26.4	6.5	1.1	0.3	0.1				
	Tech B	25 m/s						0.1	1.5	7.7	30.2	86.1	188.6	243.7	245.2	191.7	86.9	31.0	9.0	1.5	0.4	0.1				
		Moderate						0.1	1.6	7.6	29.6	84.7	185.9	241.3	242.5	188.8	84.6	29.6	8.6	1.6	0.4	0.1	0.0			
		Deep						0.1	1.4	7.2	29.0	83.9	185.2	240.6	242.2	188.2	83.0	28.7	7.8	1.3	0.4	0.1	0.0			
5.8 GW	Tech A	25 m/s				0.1	0.7	2.8	9.7	27.4	65.6	127.8	220.2	265.8	262.4	216.3	123.1	60.1	25.3	10.1	3.7	1.2	0.3	0.1		
		Moderate		0.0	0.1	0.2	0.7	2.7	9.1	26.4	63.9	125.5	218.0	264.4	261.1	214.1	120.2	57.5	23.1	8.6	2.9	0.8	0.3	0.1		
		Deep				0.1	0.5	2.4	8.7	25.7	63.1	124.6	217.7	263.9	260.8	213.8	119.3	56.4	22.3	7.9	2.4	0.5	0.2	0.1	0.0	
	Tech B	25 m/s				0.2	0.7	3.7	12.1	32.1	70.8	133.0	220.9	265.8	264.6	220.1	128.5	67.0	30.2	12.7	4.4	1.4	0.2	0.1		
		Moderate			0.0	0.3	0.9	3.5	11.4	30.7	69.2	130.3	218.2	263.6	262.6	217.1	124.8	64.1	27.8	11.0	3.5	1.1	0.3	0.1		
		Deep			0.0	0.2	0.6	3.0	11.0	30.1	68.2	129.1	217.5	263.0	262.2	216.5	123.8	62.6	26.8	10.2	3.0	0.7	0.1	0.1		

9.2.2 Intraday forecasts

Table 38 shows the average number of days per year with at least one intraday forecast error more extreme than the given GW limit. The largest forecast errors (more than +/- 1.5 GW) are slightly less likely for the Deep shutdown type compared to 25 m/s cut-off in the 4.4 GW scenarios. In the 5.8 GW scenarios, the Deep type shows a somewhat bigger benefit, with larger than 2.5 GW errors (negative or positive) occurring on 1-2 days less per year compared to 25 m/s cut-off. Similar to Section 9.1, a prediction closer to real-time reduces the occurrence of large forecast errors, also in GW. Therefore, intraday forecasts show lower errors than Day-ahead.

Table 38. Intraday forecast errors: average number of days per year with at least one event.

			Negative forecast error (GW)												Positive forecast error (GW)											
			5.5	5.0	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0	0.5	0.3	0.3	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5
0.9 GW													1.0	29.0	27.7	0.7										
2.3 GW											0.2	8.1	113.7	209.0	208.8	107.7	7.8	0.1								
3.0 GW	Tech A	25 m/s								0.1	1.9	26.6	158.7	244.3	241.1	154.3	25.3	1.7	0.1							
		Moderate								0.1	2.0	26.6	157.7	243.1	239.6	153.2	25.1	1.7	0.1							
		Deep								0.1	1.9	26.4	156.9	242.5	239.5	152.8	25.0	1.7	0.1							
	Tech B	25 m/s								0.1	1.9	26.5	159.2	245.8	242.9	155.1	25.3	1.6	0.0							
		Moderate								0.1	1.9	26.5	158.1	244.3	241.2	153.8	25.3	1.7	0.0							
		Deep								0.1	1.9	26.3	157.1	243.6	240.9	153.3	25.2	1.7	0.1							
4.4 GW	Tech A	25 m/s							0.3	2.3	15.9	77.9	214.9	279.9	279.8	212.7	77.5	15.7	2.7	0.2						
		Moderate							0.2	1.9	15.4	76.8	212.8	278.5	278.4	210.8	75.7	14.8	2.3	0.2						
		Deep							0.2	1.8	14.9	75.9	212.3	278.1	278.0	210.3	75.0	14.0	2.1	0.1						
	Tech B	25 m/s							0.3	2.6	18.7	81.3	217.3	281.0	280.6	217.9	83.3	18.0	3.0	0.2						
		Moderate						0.0	0.3	2.4	18.1	80.0	214.8	278.6	278.2	215.4	81.2	16.9	2.8	0.2						
		Deep							0.2	2.1	17.5	78.8	214.0	278.1	277.8	214.7	80.0	16.1	2.5	0.2	0.0					
5.8 GW	Tech A	25 m/s				0.0	0.2	0.9	4.1	16.0	51.5	134.5	254.3	301.5	301.4	252.7	132.1	50.4	14.9	3.7	1.3	0.4	0.1			
		Moderate			0.0	0.1	0.2	0.8	3.4	14.9	49.8	132.5	252.4	300.2	300.3	250.7	129.3	48.3	13.5	2.9	0.8	0.2	0.0			
		Deep					0.1	0.6	3.3	14.5	48.9	131.5	252.0	299.8	299.8	250.2	128.4	47.4	12.7	2.4	0.6	0.1				
	Tech B	25 m/s				0.1	0.3	1.3	5.2	19.6	57.6	141.0	254.7	302.2	304.3	255.9	139.5	58.6	19.4	5.3	1.6	0.5	0.1			
		Moderate			0.0	0.1	0.2	1.1	4.8	18.4	55.9	138.2	252.1	300.1	302.3	252.9	136.2	55.7	17.6	4.0	0.9	0.2	0.0			
		Deep				0.0	0.1	0.9	4.3	17.9	55.0	137.3	251.4	299.8	302.0	252.2	135.0	54.7	16.8	3.5	0.7	0.2	0.0	0.0		

9.2.3 Latest forecasts

Table 39 shows the average number of days per year with at least one Last forecast error more extreme than the given GW limit. Tech A and Tech B show similar statistics. The overall forecast uncertainty is slightly lower for the Deep shutdown type compared to 25 m/s cut-off. There are some extreme cases where the Deep type shows the largest forecast errors of all the storm shutdown types in the 5.8 GW scenarios. However, they are found to be related to having a large forecast error during the return from a storm event: an example is shown in Figure 30. Here these few extreme cases (around once in ten years or less) occurred for the Last forecast. However, also for the Day-ahead and Intraday, it is possible than in some cases the Deep type shows larger forecast error than 25 m/s cut-off or Moderate. Similar to Section 9.1, a prediction closer to real-time reduces the occurrence of large forecast errors also in GW: thus, Last shows less large forecast errors than Intraday.

Table 39. Last forecast errors: average number of days per year with at least one event.

			Negative forecast error (GW)												Positive forecast error (GW)											
			5.5	5.0	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0	0.5	0.3	0.3	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5
0.9 GW													0.5	10.7	9.9	0.3										
2.3 GW												2.4	76.5	196.1	198.6	75.8	1.9	0.0	0.0							
3.0 GW	Tech A	25 m/s								0.0	0.4	9.1	129.7	240.6	243.3	131.6	10.0	0.4								
		Moderate								0.0	0.4	9.0	129.0	239.5	241.9	130.7	10.0	0.4								
		Deep								0.0	0.4	9.0	128.2	238.8	241.7	130.4	9.9	0.4								
	Tech B	25 m/s								0.0	0.4	8.8	131.3	242.9	245.1	131.4	9.3	0.4								
		Moderate								0.0	0.4	8.8	130.5	241.4	243.3	131.2	9.4	0.4								
		Deep								0.0	0.4	8.8	129.5	240.5	242.9	130.3	9.3	0.4								
4.4 GW	Tech A	25 m/s							0.1	0.6	4.4	41.3	204.5	283.0	286.3	207.1	43.2	5.0	0.8	0.1	0.0					
		Moderate						0.0	0.1	0.4	4.1	40.3	202.4	281.1	284.7	205.3	42.3	4.7	0.7	0.1	0.0					
		Deep								0.3	3.8	39.6	201.7	280.6	284.4	204.5	41.3	4.2	0.5							
	Tech B	25 m/s							0.0	0.4	5.2	44.9	209.4	285.8	288.0	210.1	47.7	5.5	0.7	0.1	0.0					
		Moderate						0.0	0.1	0.3	5.0	43.6	206.7	282.9	286.0	207.8	46.5	5.2	0.8	0.2	0.0					
		Deep								0.2	4.6	42.7	205.8	282.4	285.5	206.8	45.6	4.8	0.6	0.0	0.0					
5.8 GW	Tech A	25 m/s					0.1	0.6	1.5	6.0	23.9	99.6	251.9	307.9	310.5	254.4	99.9	21.8	4.4	0.8	0.2					
		Moderate					0.2	0.5	1.3	5.1	22.2	97.2	249.6	305.9	309.3	252.2	97.6	20.5	3.7	0.5	0.2	0.0				
		Deep						0.3	0.9	4.6	21.2	96.1	249.2	305.7	308.9	251.9	96.6	19.8	3.4	0.4	0.2	0.1	0.1			
	Tech B	25 m/s				0.0	0.2	0.6	2.0	7.5	29.6	108.3	254.9	309.7	311.1	257.2	106.9	27.3	5.4	1.2	0.2					
		Moderate					0.2	0.5	1.6	6.4	27.6	105.3	251.5	307.1	308.9	254.3	104.0	25.8	4.5	0.8	0.2					
		Deep					0.2	0.3	1.2	5.6	26.6	104.0	251.0	306.6	308.5	253.5	102.7	25.0	4.1	0.6	0.1	0.1	0.0			

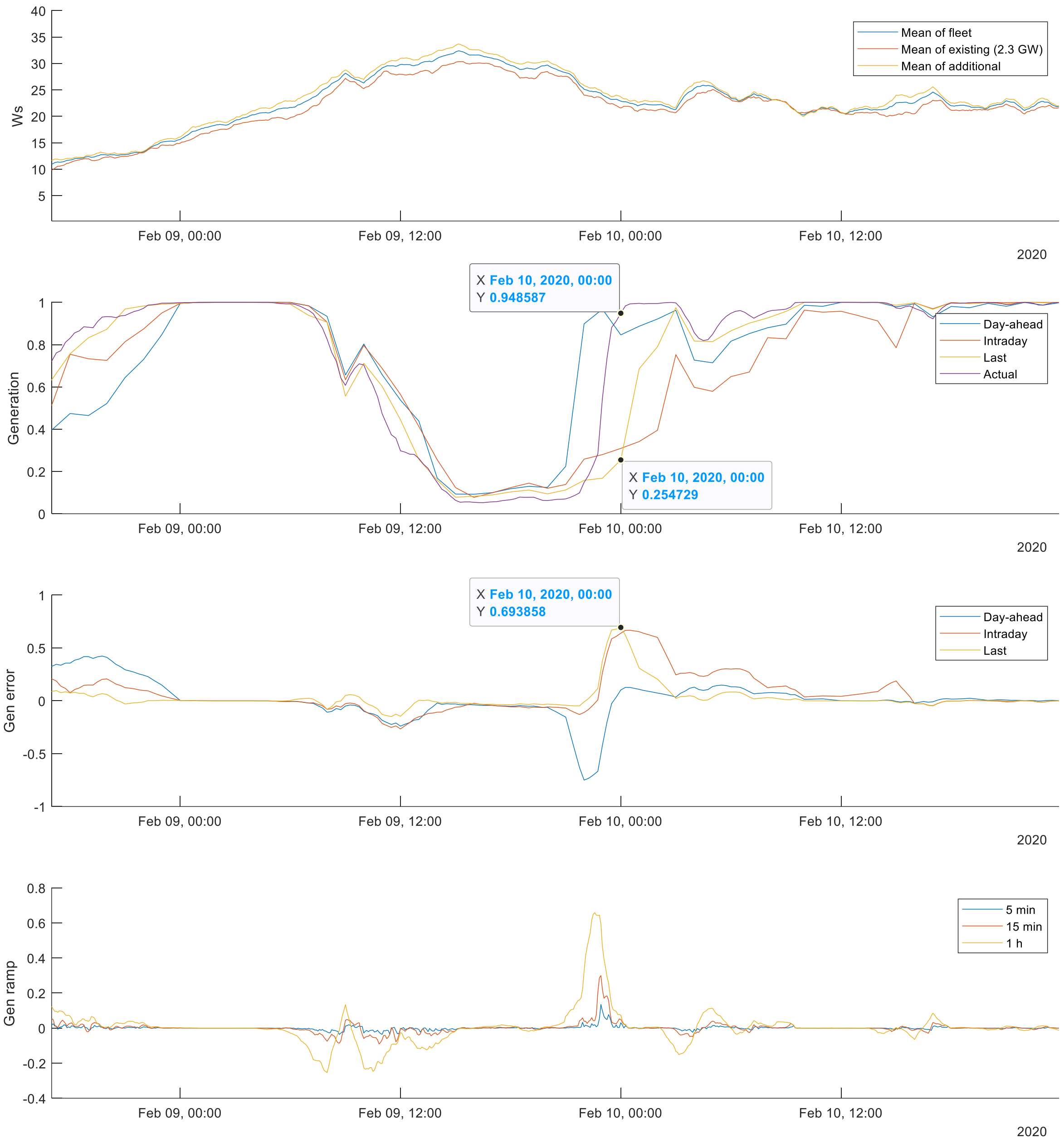

Figure 30. The simulated time series for the event with the largest Last forecast error for the 5.8 GW Tech B Deep scenario. All generation are in 15 min resolution, in standardised generation.

9.3 Forecast errors in GW during high and low wind speed days

Table 40 and Table 41 show the average number of days per year with at least one day-ahead forecast error more extreme than the given GW limit with split to high and low wind speed days, respectively. The Tech B forecast errors are slightly larger than for Tech A; however, the difference is small. For high wind speed days, the Deep type show slightly lower likelihoods for very high forecast errors (larger than 2.5 GW, either positive or negative) compared to 25 m/s cut-off. The capability of the Deep type to reduce generation forecast uncertainty (even as the quality of wind speed forecasts is the same) relates to error in wind speed having a different impact on the generation forecast error. This can be seen in Figure 4: if forecasted wind speed is 24 m/s, but actual wind speed is 28 m/s (and we assume that we are not yet in a storm shutdown), the error in generation for the 25 m/s cut-off is 100 %, whereas for the Deep type the generation error is less than 50 % (note that this example is for a single OWPP; however, the principle holds for fleet-level).

Comparing the day-ahead forecast errors on high (Table 40) and low wind speed days (Table 41), the largest forecast errors (above 4.5 GW) occur only on high wind speed days. Looking at the 5.8 GW scenarios, the likelihoods of large day-ahead forecast errors (above 3.5 GW) are relatively similar for both the low and high wind speed days (between 0.1 and 0.9 days per year, for negative and positive forecast errors, respectively). Considering that the high wind speed days represent only about 7 % of all days, the large forecast errors are thus more likely on high wind speed days (i.e., the relative frequency of large forecast errors is higher on high wind speed than on low wind speed day).

Table 42 and Table 43 show similar results as discussed above, but for intraday forecasts, and Table 44 and Table 45 show them for the Last forecasts. The differences between Tech A and Tech B and between the different storm shutdown types are similar as for day-ahead (overall, the forecast errors are of course somewhat lower than for day-ahead, as expected based on the previous sections).

Day-ahead forecasts:

Table 40. Day-ahead forecast errors: average number of days per year with at least one event when the daily max fleet-level wind speed is above 20 m/s.

			Negative forecast error (GW)												Positive forecast error (GW)											
			5.5	5.0	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0	0.5	0.3	0.3	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5
2.3 GW (existing)											0.1	0.5	3.9	7.3	9.2	5.4	1.0	0.1	0.1							
3.0 GW	Tech A	25 m/s								0.0	0.3	1.7	7.2	11.1	12.6	8.6	2.3	0.6	0.1	0.0						
		Moderate								0.1	0.3	1.7	6.2	9.7	11.2	7.2	2.1	0.6	0.1	0.0						
		Deep							0.0	0.0	0.2	1.4	5.7	9.1	10.8	6.6	1.8	0.5	0.1	0.0						
	Tech B	25 m/s								0.0	0.2	1.5	7.3	11.5	13.7	9.1	2.2	0.5	0.1	0.0						
		Moderate								0.1	0.3	1.6	6.3	9.7	11.4	7.3	2.1	0.6	0.2	0.0						
		Deep							0.0	0.1	0.2	1.4	5.5	9.0	11.1	6.6	1.8	0.5	0.1	0.0						
4.4 GW	Tech A	25 m/s							0.2	0.6	1.7	4.4	9.6	12.6	14.9	12.5	7.4	3.8	1.7	0.4	0.2	0.1				
		Moderate						0.0	0.1	0.4	1.1	3.2	7.6	11.1	13.5	10.5	5.0	2.4	1.1	0.3	0.2	0.1	0.0			
		Deep								0.1	0.5	2.5	7.2	10.7	13.2	10.0	4.1	1.5	0.5	0.2	0.1	0.1				
	Tech B	25 m/s							0.1	0.7	1.9	4.8	10.4	13.8	17.2	13.7	7.8	4.0	1.9	0.4	0.1	0.0				
		Moderate							0.2	0.6	1.3	3.5	7.9	11.5	14.6	10.9	5.5	2.6	1.5	0.5	0.2	0.1	0.0			
		Deep								0.2	0.7	2.6	7.2	10.9	14.4	10.4	4.0	1.6	0.7	0.1	0.1	0.1	0.0			
5.8 GW	Tech A	25 m/s				0.1	0.3	0.6	1.4	2.7	4.7	7.7	12.6	14.6	17.2	14.5	9.8	6.4	4.2	2.7	1.5	0.9	0.2	0.1		
		Moderate		0.0	0.1	0.2	0.3	0.5	0.9	1.6	3.0	5.4	10.4	13.3	16.0	12.5	7.0	3.8	2.0	1.2	0.8	0.5	0.3	0.1		
		Deep				0.1	0.1	0.2	0.4	1.0	2.2	4.5	10.1	12.8	15.7	12.1	6.1	2.8	1.2	0.5	0.3	0.2	0.1	0.1	0.0	
	Tech B	25 m/s				0.1	0.2	0.9	1.7	3.1	5.2	8.6	13.5	16.0	18.7	16.3	11.4	7.6	4.9	3.3	1.9	0.9	0.2	0.1		
		Moderate			0.0	0.2	0.4	0.6	1.0	1.7	3.5	5.9	10.8	13.8	16.9	13.4	7.7	4.7	2.5	1.6	1.0	0.5	0.3	0.1		
		Deep			0.0	0.1	0.1	0.2	0.6	1.1	2.5	4.7	10.2	13.2	16.5	12.8	6.7	3.2	1.6	0.8	0.4	0.2	0.1	0.1		

Table 41. Day-ahead forecast errors: average number of days per year with at least one event when the daily max fleet-level wind speed is below 20 m/s.

			Negative forecast error (GW)												Positive forecast error (GW)											
			5.5	5.0	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0	0.5	0.3	0.3	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5
2.3 GW (existing)											0.7	18.9	106.2	174.2	172.0	102.7	16.8	0.7								
3.0 GW	Tech A	25 m/s								0.4	6.4	38.7	135.1	198.0	196.8	132.5	37.6	5.5	0.2							
		Moderate								0.4	6.4	38.7	135.1	198.0	196.7	132.4	37.6	5.5	0.2							
		Deep								0.4	6.4	38.7	135.1	198.0	196.7	132.4	37.6	5.5	0.2							
	Tech B	25 m/s								0.5	6.5	39.0	135.6	198.3	198.1	133.6	37.5	5.4	0.3							
		Moderate								0.5	6.5	39.0	135.6	198.2	197.8	133.5	37.5	5.4	0.3							
		Deep								0.5	6.5	39.0	135.6	198.2	197.8	133.5	37.5	5.4	0.3							
4.4 GW	Tech A	25 m/s						0.1	1.0	6.2	26.8	79.2	176.9	229.3	227.4	174.8	76.1	25.0	6.0	1.0	0.2	0.0				
		Moderate						0.1	1.0	6.2	26.8	79.2	176.8	229.3	227.2	174.7	76.1	25.0	6.0	1.0	0.2	0.0				
		Deep						0.1	1.0	6.2	26.8	79.2	176.8	229.2	227.2	174.7	76.1	25.0	6.0	1.0	0.2	0.0				
	Tech B	25 m/s						0.1	1.4	7.0	28.3	81.3	178.1	229.9	228.1	178.0	79.1	27.0	7.1	1.1	0.3	0.1				
		Moderate						0.1	1.4	7.0	28.3	81.3	178.0	229.8	227.9	177.9	79.1	27.0	7.1	1.1	0.3	0.1				
		Deep						0.1	1.4	7.0	28.3	81.3	178.0	229.8	227.9	177.9	79.1	27.0	7.1	1.1	0.3	0.1				
5.8 GW	Tech A	25 m/s				0.1	0.5	2.2	8.3	24.8	60.9	120.1	207.6	251.2	245.2	201.8	113.3	53.7	21.1	7.4	2.1	0.3	0.0			
		Moderate				0.1	0.5	2.2	8.3	24.8	60.9	120.1	207.6	251.1	245.1	201.7	113.2	53.7	21.1	7.4	2.1	0.3	0.0			
		Deep				0.1	0.5	2.2	8.3	24.8	60.9	120.1	207.6	251.1	245.1	201.7	113.2	53.7	21.1	7.4	2.1	0.3	0.0			
	Tech B	25 m/s				0.1	0.5	2.9	10.4	29.0	65.7	124.4	207.4	249.8	245.9	203.8	117.1	59.4	25.3	9.4	2.6	0.6	0.0			
		Moderate				0.1	0.5	2.9	10.4	29.0	65.7	124.4	207.3	249.8	245.7	203.7	117.1	59.3	25.2	9.4	2.6	0.6	0.0			
		Deep				0.1	0.5	2.9	10.4	29.0	65.7	124.4	207.3	249.8	245.7	203.7	117.1	59.3	25.2	9.4	2.6	0.6	0.0			

Intraday forecasts:

Table 42. Intraday forecast errors: average number of days per year with at least one event when the daily max fleet-level wind speed is above 20 m/s.

			Negative forecast error (GW)												Positive forecast error (GW)											
			5.5	5.0	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0	0.5	0.3	0.3	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5
2.3 GW (existing)											0.0	0.2	4.0	7.4	8.6	4.8	0.5	0.0								
3.0 GW	Tech A	25 m/s								0.0	0.1	1.1	7.5	11.6	12.3	7.5	1.3	0.1								
		Moderate								0.0	0.2	1.1	6.4	10.5	10.9	6.4	1.1	0.1	0.0							
		Deep								0.0	0.1	0.8	5.7	9.9	10.8	6.0	0.9	0.1	0.0							
	Tech B	25 m/s								0.0	0.1	1.1	7.6	12.3	12.6	7.9	1.2	0.1								
		Moderate								0.0	0.1	1.1	6.5	10.8	10.9	6.5	1.1	0.1								
		Deep								0.0	0.1	1.0	5.7	10.1	10.6	6.0	1.0	0.2	0.0							
4.4 GW	Tech A	25 m/s							0.2	0.7	1.4	4.3	10.2	12.9	14.9	11.9	6.0	2.5	0.9	0.1						
		Moderate							0.1	0.3	0.9	3.2	8.2	11.5	13.5	9.9	4.1	1.6	0.6	0.1						
		Deep								0.1	0.4	2.3	7.7	11.2	13.1	9.5	3.4	0.8	0.3	0.0						
	Tech B	25 m/s							0.1	0.6	1.7	4.7	11.1	14.2	16.2	13.1	6.6	2.8	0.9	0.1						
		Moderate						0.0	0.1	0.5	1.2	3.4	8.8	11.9	13.8	10.6	4.5	1.8	0.6	0.2						
		Deep								0.1	0.5	2.3	7.9	11.4	13.4	9.9	3.3	1.0	0.4	0.1	0.0					
5.8 GW	Tech A	25 m/s				0.0	0.2	0.4	1.2	2.2	4.1	7.6	12.9	15.6	16.7	14.2	9.1	5.1	2.7	1.5	0.8	0.4	0.1			
		Moderate			0.0	0.1	0.1	0.3	0.5	1.1	2.4	5.6	11.0	14.3	15.6	12.2	6.4	3.0	1.4	0.7	0.3	0.1	0.0			
		Deep						0.1	0.3	0.7	1.5	4.6	10.6	13.9	15.1	11.7	5.4	2.1	0.6	0.2	0.1	0.1				
	Tech B	25 m/s				0.0	0.2	0.5	1.2	2.5	4.7	8.1	13.8	16.5	18.7	15.9	10.4	6.5	3.5	2.1	1.1	0.4	0.1			
		Moderate			0.0	0.1	0.2	0.3	0.7	1.3	2.9	5.4	11.2	14.5	16.7	12.9	7.1	3.6	1.7	0.8	0.4	0.1	0.0			
		Deep					0.0	0.1	0.3	0.8	2.0	4.4	10.5	14.2	16.4	12.2	5.9	2.5	0.9	0.3	0.2	0.1	0.0	0.0		

Table 43. Intraday forecast errors: average number of days per year with at least one event when the daily max fleet-level wind speed is below 20 m/s.

			Negative forecast error (GW)												Positive forecast error (GW)											
			5.5	5.0	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0	0.5	0.3	0.3	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5
2.3 GW (existing)											0.1	7.9	109.7	201.7	200.2	102.9	7.3	0.1								
3.0 GW	Tech A	25 m/s								0.1	1.8	25.6	151.3	232.7	228.7	146.8	24.1	1.6	0.1							
		Moderate								0.1	1.8	25.6	151.3	232.7	228.7	146.8	24.1	1.6	0.1							
		Deep								0.1	1.8	25.6	151.3	232.6	228.7	146.8	24.1	1.6	0.1							
	Tech B	25 m/s								0.1	1.8	25.3	151.6	233.6	230.3	147.3	24.2	1.6	0.0							
		Moderate								0.1	1.8	25.3	151.5	233.5	230.3	147.3	24.2	1.6	0.0							
		Deep								0.1	1.8	25.3	151.5	233.5	230.3	147.3	24.2	1.6	0.0							
4.4 GW	Tech A	25 m/s							0.2	1.7	14.5	73.6	204.7	267.0	264.9	200.9	71.6	13.2	1.7	0.1						
		Moderate							0.2	1.7	14.5	73.6	204.6	267.0	264.9	200.9	71.6	13.2	1.7	0.1						
		Deep							0.2	1.7	14.5	73.6	204.6	267.0	264.9	200.9	71.6	13.2	1.7	0.1						
	Tech B	25 m/s							0.2	2.0	17.0	76.5	206.2	266.7	264.5	204.8	76.7	15.2	2.1	0.1						
		Moderate							0.2	2.0	17.0	76.5	206.1	266.7	264.4	204.8	76.7	15.2	2.1	0.1						
		Deep							0.2	2.0	17.0	76.5	206.1	266.7	264.4	204.8	76.7	15.2	2.1	0.1						
5.8 GW	Tech A	25 m/s					0.1	0.5	3.0	13.8	47.4	126.9	241.4	286.0	284.7	238.5	123.0	45.3	12.2	2.2	0.5	0.0				
		Moderate					0.1	0.5	3.0	13.8	47.4	126.9	241.4	285.9	284.7	238.5	123.0	45.3	12.2	2.2	0.5	0.0				
		Deep					0.1	0.5	3.0	13.8	47.4	126.9	241.4	285.9	284.7	238.5	123.0	45.3	12.2	2.2	0.5	0.0				
	Tech B	25 m/s				0.0	0.1	0.8	4.1	17.1	53.0	132.9	240.9	285.6	285.6	240.0	129.1	52.1	15.9	3.2	0.5	0.1				
		Moderate				0.0	0.1	0.8	4.1	17.1	53.0	132.9	240.9	285.6	285.6	240.0	129.1	52.1	15.9	3.2	0.5	0.1				
		Deep				0.0	0.1	0.8	4.1	17.1	53.0	132.9	240.9	285.6	285.6	240.0	129.1	52.1	15.9	3.2	0.5	0.1				

Last forecasts:

Table 44. Last forecast errors: average number of days per year with at least one event when the daily max fleet-level wind speed is above 20 m/s.

			Negative forecast error (GW)												Positive forecast error (GW)											
			5.5	5.0	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0	0.5	0.3	0.3	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5
2.3 GW (existing)												0.2	2.9	7.0	7.2	3.0	0.2	0.0	0.0							
3.0 GW	Tech A	25 m/s									0.0	0.7	6.1	11.5	11.2	5.7	0.5	0.0								
		Moderate									0.0	0.7	5.4	10.5	9.8	4.7	0.5	0.0								
		Deep									0.0	0.6	4.7	9.8	9.6	4.4	0.4	0.0								
	Tech B	25 m/s									0.0	0.6	6.6	12.3	11.7	5.4	0.4	0.0								
		Moderate									0.0	0.6	5.7	10.9	9.9	5.2	0.5	0.1								
		Deep									0.1	0.5	4.8	10.0	9.5	4.2	0.3	0.0								
4.4 GW	Tech A	25 m/s							0.1	0.4	0.9	3.2	10.1	13.7	14.2	10.3	3.6	1.0	0.4	0.1	0.0					
		Moderate						0.0	0.1	0.2	0.6	2.2	8.1	11.8	12.6	8.5	2.7	0.7	0.3	0.1	0.0					
		Deep								0.0	0.2	1.4	7.3	11.4	12.3	7.6	1.7	0.3	0.1							
	Tech B	25 m/s							0.0	0.2	0.9	3.8	11.1	15.3	14.6	10.9	3.9	1.1	0.3	0.1	0.0					
		Moderate						0.0	0.1	0.2	0.6	2.5	8.5	12.3	12.6	8.7	2.8	0.8	0.4	0.2	0.0					
		Deep								0.0	0.2	1.6	7.6	11.8	12.1	7.8	1.8	0.4	0.2	0.0	0.0					
5.8 GW	Tech A	25 m/s					0.1	0.4	0.8	1.8	3.7	7.0	13.2	16.3	16.2	13.3	6.6	2.8	1.3	0.5	0.2					
		Moderate					0.2	0.3	0.7	1.0	2.0	4.7	11.0	14.3	15.1	11.1	4.3	1.5	0.6	0.3	0.1	0.0				
		Deep						0.1	0.2	0.4	1.0	3.6	10.6	14.1	14.6	10.8	3.4	0.8	0.3	0.1	0.1	0.1	0.1			
	Tech B	25 m/s				0.0	0.1	0.4	1.1	2.2	4.4	8.1	14.7	17.8	17.7	14.4	7.6	3.4	1.7	0.7	0.1					
		Moderate					0.1	0.3	0.7	1.2	2.4	5.2	11.3	15.3	15.5	11.4	4.6	1.9	0.8	0.3	0.1					
		Deep					0.1	0.1	0.2	0.4	1.4	3.8	10.8	14.8	15.1	10.7	3.3	1.1	0.4	0.1	0.1	0.1	0.0			

Table 45. Last forecast errors: average number of days per year with at least one event when the daily max fleet-level wind speed is below 20 m/s.

			Negative forecast error (GW)												Positive forecast error (GW)											
			5.5	5.0	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0	0.5	0.3	0.3	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5
2.3 GW (existing)												2.3	73.6	189.2	191.4	72.8	1.7									
3.0 GW	Tech A	25 m/s								0.0	0.4	8.4	123.6	229.1	232.1	126.0	9.5	0.4								
		Moderate								0.0	0.4	8.4	123.6	229.1	232.1	126.0	9.5	0.4								
		Deep								0.0	0.4	8.4	123.6	229.0	232.1	126.0	9.5	0.4								
	Tech B	25 m/s								0.0	0.4	8.2	124.7	230.6	233.4	126.1	8.9	0.4								
		Moderate								0.0	0.4	8.2	124.7	230.5	233.4	126.1	8.9	0.4								
		Deep								0.0	0.4	8.2	124.7	230.5	233.4	126.1	8.9	0.4								
4.4 GW	Tech A	25 m/s								0.2	3.6	38.2	194.4	269.3	272.2	196.9	39.6	4.0	0.4							
		Moderate								0.2	3.6	38.2	194.3	269.3	272.1	196.8	39.6	4.0	0.4							
		Deep								0.2	3.6	38.2	194.3	269.2	272.1	196.8	39.6	4.0	0.4							
	Tech B	25 m/s								0.2	4.3	41.1	198.3	270.6	273.5	199.1	43.8	4.5	0.4							
		Moderate								0.2	4.3	41.1	198.2	270.6	273.4	199.1	43.8	4.5	0.4							
		Deep								0.2	4.3	41.1	198.2	270.5	273.4	199.1	43.8	4.5	0.4							
5.8 GW	Tech A	25 m/s						0.2	0.7	4.2	20.2	92.6	238.7	291.6	294.3	241.1	93.3	19.0	3.1	0.3	0.0					
		Moderate						0.2	0.7	4.2	20.2	92.6	238.6	291.6	294.3	241.1	93.3	19.0	3.1	0.3	0.0					
		Deep						0.2	0.7	4.2	20.2	92.6	238.6	291.6	294.3	241.1	93.3	19.0	3.1	0.3	0.0					
	Tech B	25 m/s					0.1	0.2	0.9	5.2	25.2	100.2	240.2	291.8	293.4	242.9	99.4	23.9	3.7	0.5	0.1					
		Moderate					0.1	0.2	0.9	5.2	25.2	100.2	240.2	291.8	293.4	242.9	99.4	23.9	3.7	0.5	0.1					
		Deep					0.1	0.2	0.9	5.2	25.2	100.2	240.2	291.8	293.4	242.9	99.4	23.9	3.7	0.5	0.1					

9.4 Forecast errors during high ramp and storm days

9.4.1 High ramp and storm days

High ramp days are defined as days with a maximum ramp > 2 GW (either negative or positive) where the most extreme of the 5 min, 15 min and 1 h ramp defines the maximum ramp of the day. These days are listed for the simulations and provided to Elia. For the purpose of this analysis, storm days are defined as high ramp days where max wind speed of the day is above 20 m/s. The storm days are also listed and provided to Elia.

Average days per year of the high ramp and storm days are given in Table 46. For the 4.4 GW and 5.8 GW scenarios, where the additional installations constitute a significant share of the total fleet, the Deep type shows significantly less storm days with high ramp compared to the 25 m/s cut-off shutdown type; even though wind speeds are the same for both storm shutdown types, the Deep type experiences less days with high ramp. This is in line with Table 33: the likelihood of higher than 2 GW ramp is reduced for Deep compared to 25 m/s cut-off. In Table 46, Tech B shows some increase in the average number of days per year compared to Tech A.

Table 46. Average number of high ramp and storm days per year.

			Average number of days per year:	
			High ramp days	**Storm days with high ramp**
3.0 GW	**Tech A**	**25 m/s**	0.7	0.5
		Moderate	0.9	0.6
		Deep	0.7	0.5
	Tech B	**25 m/s**	0.6	0.4
		Moderate	0.8	0.6
		Deep	0.8	0.5
4.4 GW	**Tech A**	**25 m/s**	9.1	4.7
		Moderate	7.2	2.8
		Deep	6.0	1.6
	Tech B	**25 m/s**	10.0	5.2
		Moderate	8.1	3.3
		Deep	6.6	1.7
5.8 GW	**Tech A**	**25 m/s**	31.3	8.7
		Moderate	28.1	5.5
		Deep	26.6	4.0
	Tech B	**25 m/s**	39.4	10.3
		Moderate	35.6	6.5
		Deep	33.5	4.5

9.4.2 Daily extreme forecast errors during high ramp days

Figure 31 shows the distributions of min and max forecast errors of the day for all simulated days, and for high ramp days (ramp > 2 GW) for the 5.8 GW Deep scenario. For all forecast horizons, the high ramp days show slightly increased likelihood for high forecast error (the error distribution moves further from zero).

Table 47 shows that high (> 40 % of installed capacity) negative and positive DA forecast errors are more likely during high ramp days. The Deep type shows significantly lower forecast errors during high ramp days compared to 25 m/s cut-off. It should be noted that the statistics reported in the table for the high ramp days are uncertain, as only a small number of days from the simulated 40 years have both a large ramp and a large forecast error on the same day (on average 32 days for the 4.4 GW scenarios, and 111 days for the 5.8 GW scenarios).

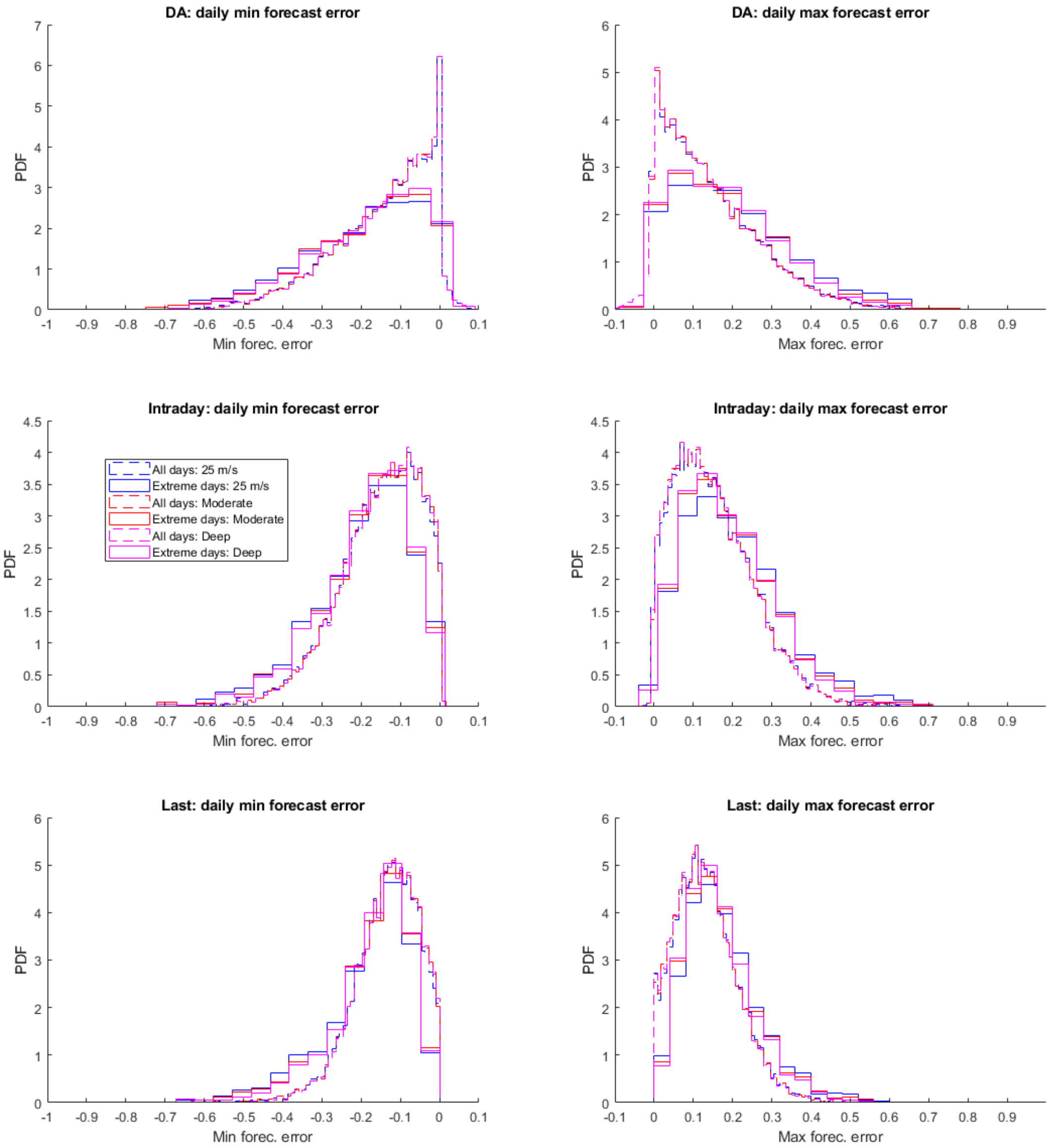

Figure 31. Distributions of max and mix forecast error of the day for all simulated days and for high ramp days (noted "extreme days" in the figure) for 5.8 GW Tech B.

Table 47. Share of days with maximum day-ahead forecast error below -0.4 or above 0.4 in standardized generation: comparison of all days and high ramp days.

			Number of days:		Share of days with forecast err. < -0.4:		Share of days with forecast err. > 0.4:	
			All days	High ramp days	All days	High ramp days	All days	High ramp days
4.4 GW	**Tech A**	**25 m/s**	14610	335	4%	9%	4%	17%
		Moderate	14610	267	4%	7%	4%	15%
		Deep	14610	221	4%	3%	4%	11%
	Tech B	**25 m/s**	14610	371	4%	9%	4%	16%
		Moderate	14610	301	4%	9%	4%	15%
		Deep	14610	243	4%	4%	4%	12%
5.8 GW	**Tech A**	**25 m/s**	14610	1158	4%	11%	4%	10%
		Moderate	14610	1039	4%	9%	3%	8%
		Deep	14610	984	4%	8%	3%	6%
	Tech B	**25 m/s**	14610	1457	5%	11%	5%	11%
		Moderate	14610	1316	5%	10%	4%	9%
		Deep	14610	1239	5%	9%	4%	8%

9.4.3 Daily extreme forecast errors during storm days

Figure 32 shows the distributions of min and max forecast errors of the day for all simulated days and for storm days for 5.8 GW Tech B scenarios. It can be seen that for all forecast horizons, the storm days show somewhat increased likelihood for high forecast error (distributions further from zero). However, the estimation of forecast error distributions for storm days is challenging due to relatively small number of days falling into the storm definition (see Section 9.4.1), as can be seen in Table 46.

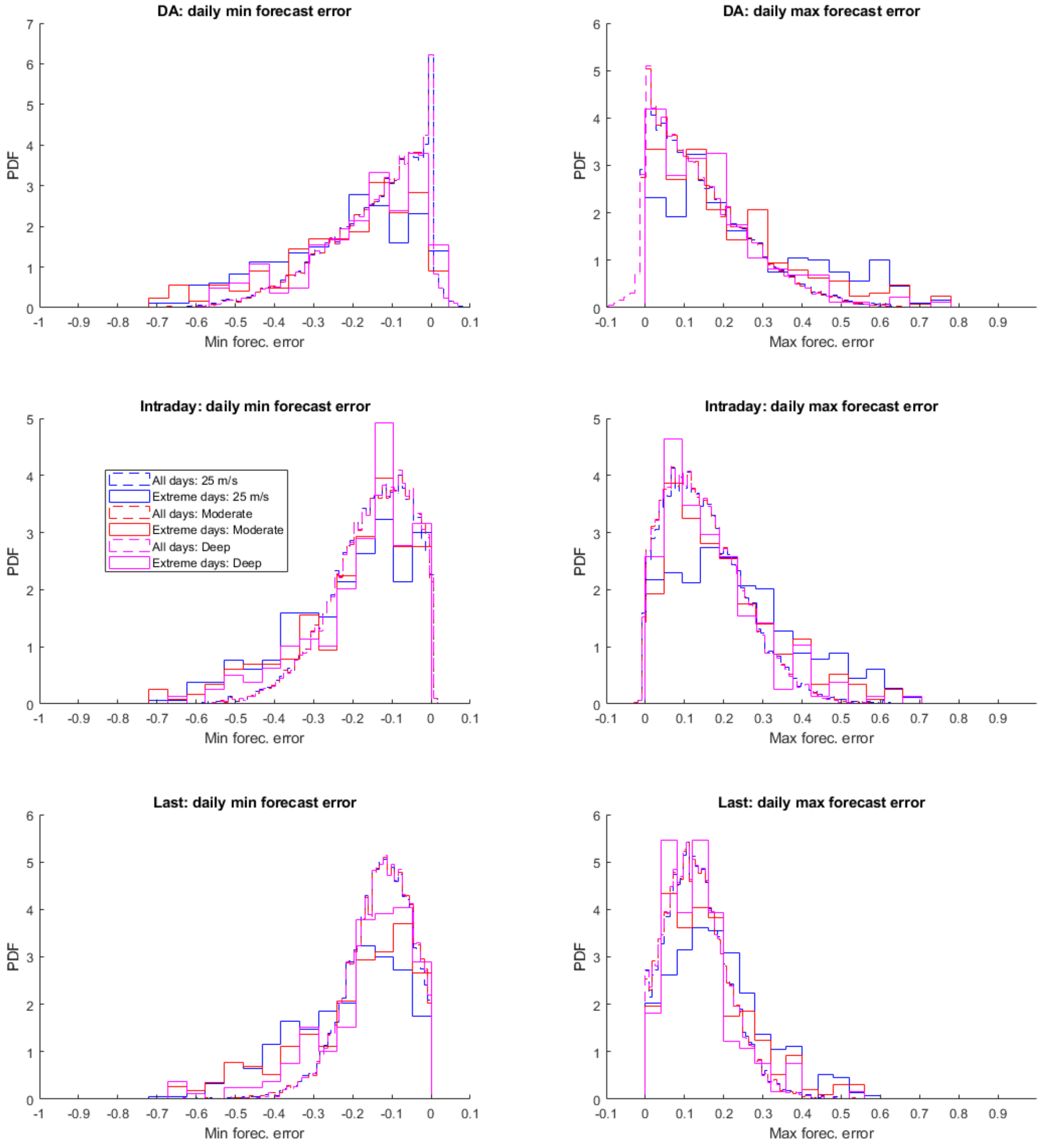

Figure 32. Distributions of max and mix forecast error of the day for all simulated days and for storm days with high ramp (noted "extreme days" in the figure) for 5.8 GW Tech B scenarios.

9.5 Conclusions on forecast errors

The fleet-level SD of standardized forecast errors decreases from the 0.9 GW scenarios towards the 5.8 GW scenarios. This is driven by increased geographical spread of installations and is particularly related to the locations of the new offshore wind installations being on the other side of the Belgian offshore region compared to the existing installations, as seen in Figure 2 (no change in the forecasting accuracy of a single OWPP was assumed). Day-ahead forecast errors of more than 3.0 GW (negative or positive) are expected to occur a few days a year in the 5.8 GW scenarios, whereas for the latest available forecasts such errors occur on less than 1 day a year. In the 40-year simulation, positive day-ahead forecast errors larger than 4.5 GW are seen for all 5.8 GW scenarios (0.1 days/year), and negative day-ahead forecast errors larger than 4.5 GW are seen for half of the 5.8 GW scenarios. For the last forecasts, larger than 4.5 GW forecast errors (positive or negative) are not seen in the simulated data.

Looking at latest available forecast errors larger than 2.5 GW in the 5.8 GW scenarios, the Deep type shows on average slightly lower errors compared to the 25 m/s cut-off. The capability of the Deep type to reduce generation forecast uncertainty (even as the quality of wind speed forecasts is the same) relates to error in wind speed having a different impact on the generation forecast error for wind speeds above 24 m/s. However, the Deep type shows some of the most extreme forecast errors for the last forecasts which is explained by having a large forecast error during the return from a storm event.

Days with high ramps (> 2 GW) show higher forecast errors compared to all days on average. Storm days (max wind speed > 20 m/s and ramp > 2 GW) show higher forecast errors than all days on average; however, due to relatively small amount of storm days, the representativeness of forecast error distributions is challenging.

It needs to be noted that forecasts are difficult to simulate than as the target is not to replicate the variability due to weather, but to try to represent the forecasts by the Elia’s forecast provider and to then estimate forecast behaviour in future scenarios. For this reason, the results presented for forecasts and forecast errors for the extended capacity scenarios need to be taken as representing average changes in the forecast errors resulting from different geographical installation distributions and storm shutdown technologies. The actual simulated forecast and forecast error values for an individual event are stochastic and can be high or low due to randomness.

Annex - Time series data provided for Elia

In addition to this report, the simulated time series from are provided for Elia.

Simulations:
This folder includes the simulated time series from CorRES for the entire time range of 1982 to 2021 included. Subfolder “Aggregated_pow_and_ws” includes the simulated generation and wind speed data aggregated for the different scenarios, both on 5 min and 15 min resolution. For the future scenarios (i.e., more than 2.3 GW), the aggregated results are split to the Existing part (2.3 GW) and Additional part (the installations on top of the existing 2.3 GW). Subfolder “Aggregated_forecasts_pow_15min” includes the simulated forecasts on 15 min resolution. The “Individual_OWPPs” folder gives the simulated time series for each OWPP.

All generation data in the files are given in standardized generation, i.e., a value of “1” means that the plant, or aggregate generation for the aggregate data files, is generating at full installed capacity. Wind speeds are given in m/s.

Extreme_ramps_and_storm_events:
The data in this folder are based on the time series in the “Simulations” folder. Those data are analysed to create the different “ramp_events_freq_in_days_per_year” files: these files show how many days per year can be expected to have (at least 1) ramp event over a given limit based on the 40 years of simulations. All data are analysed in 5 min resolution. The files include sheets with all days considered, and split to days when the maximum wind speed of the day is higher or lower than 20 m/s.

The files “Extreme_ramp_events_selected” and “Storm_events_selected” report the most extreme ramp and storm cases based on the 40 years of simulations. The extreme ramp days are days when the maximum ramp (up- or down-ramp) is larger than 2 GW. The most extreme of the 5 min, 15 min and 1 h ramp defines the maximum ramp of the day. Storm days are defined as high ramp days where max wind speed of the day is above 20 m/s. In the file “Storm_events_selected”, the columns Storm_start and Storm_end are calculated looking also one day before and one day after the specific date (row) in the Excel, to capture storms lasting beyond midnight (and thus falling on two days). The following columns DuringStorm_minGeneration_GW, DuringStorm_minGenerationTime, DuringStorm_maxWindSpeed, and DuringStorm_maxWindSpeedTime relate to values occurring between the storm start and end time. The subsequent columns related to the specific date.

Extreme_events_1min_interpolations:
This folder provides interpolated 1 min resolution time series for the extreme ramp and storm cases listed in “Extreme_ramp_events_selected” and “Storm_events_selected” (see above). In addition to the specific extreme ramp/storm day, the previous and the subsequent day are included in 1 min resolution.

Generation_and_forecast_2018-2021:
This folder includes the latest years (2018-2021) for easier access (compared to opening a file with all the 40 years). Most of the data are the same as mentioned above, but organised in a slightly different way, based on Elia’s request. However, in the subfolder “Filter_generation_and_forecast_2018-2021_SCALED” the forecast time series are handled as described in Section 4.4 (the actual generation time series and wind speed time series are the same as mentioned above).

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