Task Force MOG 2

24.06.2022

Agenda

Task Force MOG 2 24/06

EDS preparation

Session 1

10h00 -12h30

Connection requirements

[75 min]

Overview of technical specification/interface

Overview of technical specifications (island overview, grid design 66kV, interface point, testing requirement 66kV, protection concept/philosophy, wind park control cubicles)

Dynamic & Harmonic

[75 min]

Presentation of system impact and need for studies as preparation for 1st OWF tendering

Main challenge of massive integration of power electronic converters in the Belgian coast area from power system stability perspective

Session 2

13h30 - 16h00

Balancing

[75 min]

Update on MOG 2 system integration study

- *General status of the study;*
- *Results on the simulation of the wind power generation profiles;*
- *Methodology for the impact assessment on balancing.*

Workshop

Market Design

[60 min]

Follow-up discussion

- *Follow-up on market implication of creating an offshore bidding zone;*
- *Introduction on balancing implication of creating an offshore bidding zone.*

Connection requirements

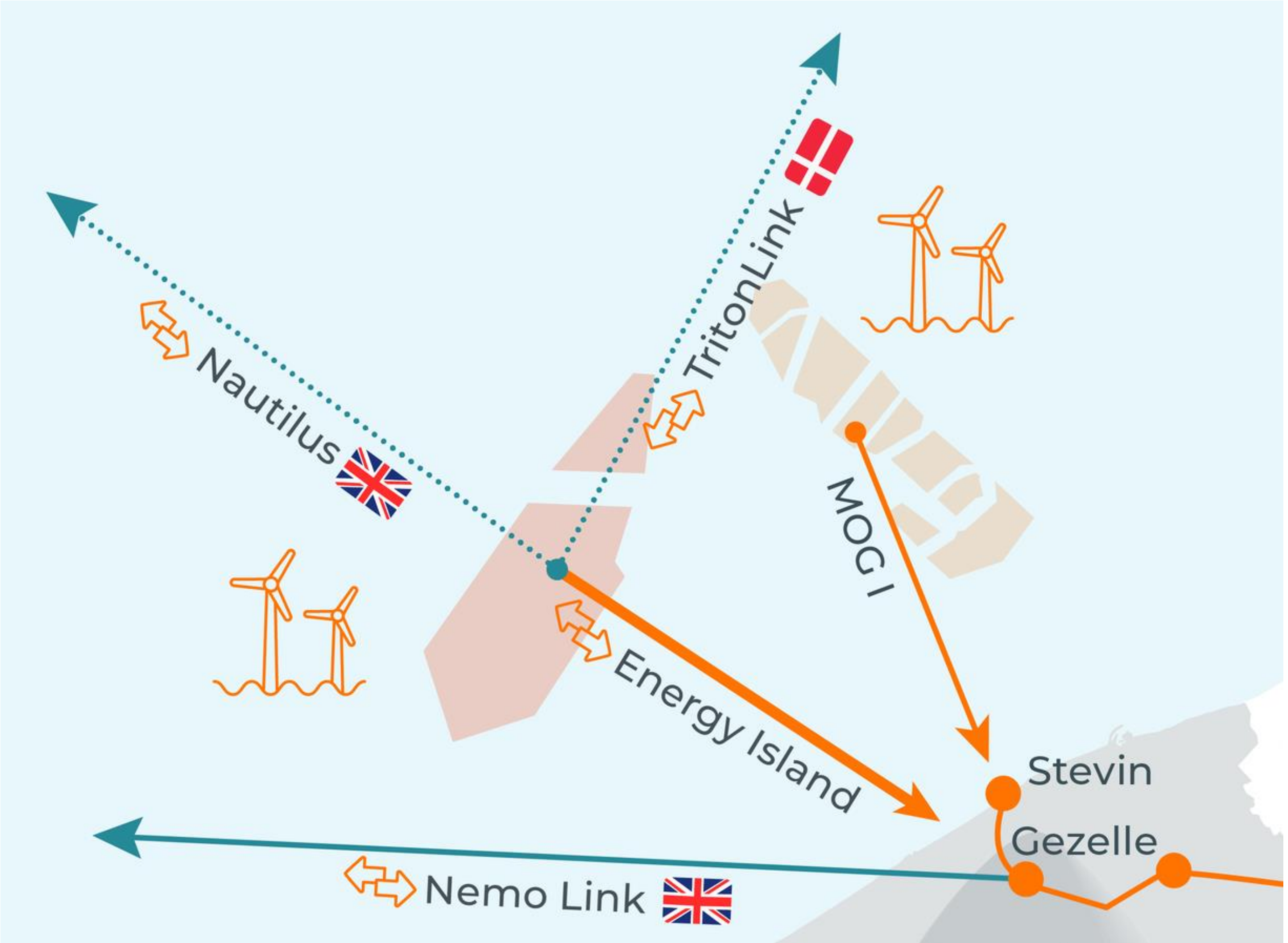
Agenda

1. Context
2. Island concept
3. Grid design
4. Interface point & protection concept
5. Windfarm control cubicles
6. Testing requirements Array cables

Context

Tom Trappeniers
Davy Verwilghen

Offshore Tomorrow : more offshore wind & first energy island



Creation of an offshore energy transmission hub in the form of an artificial island

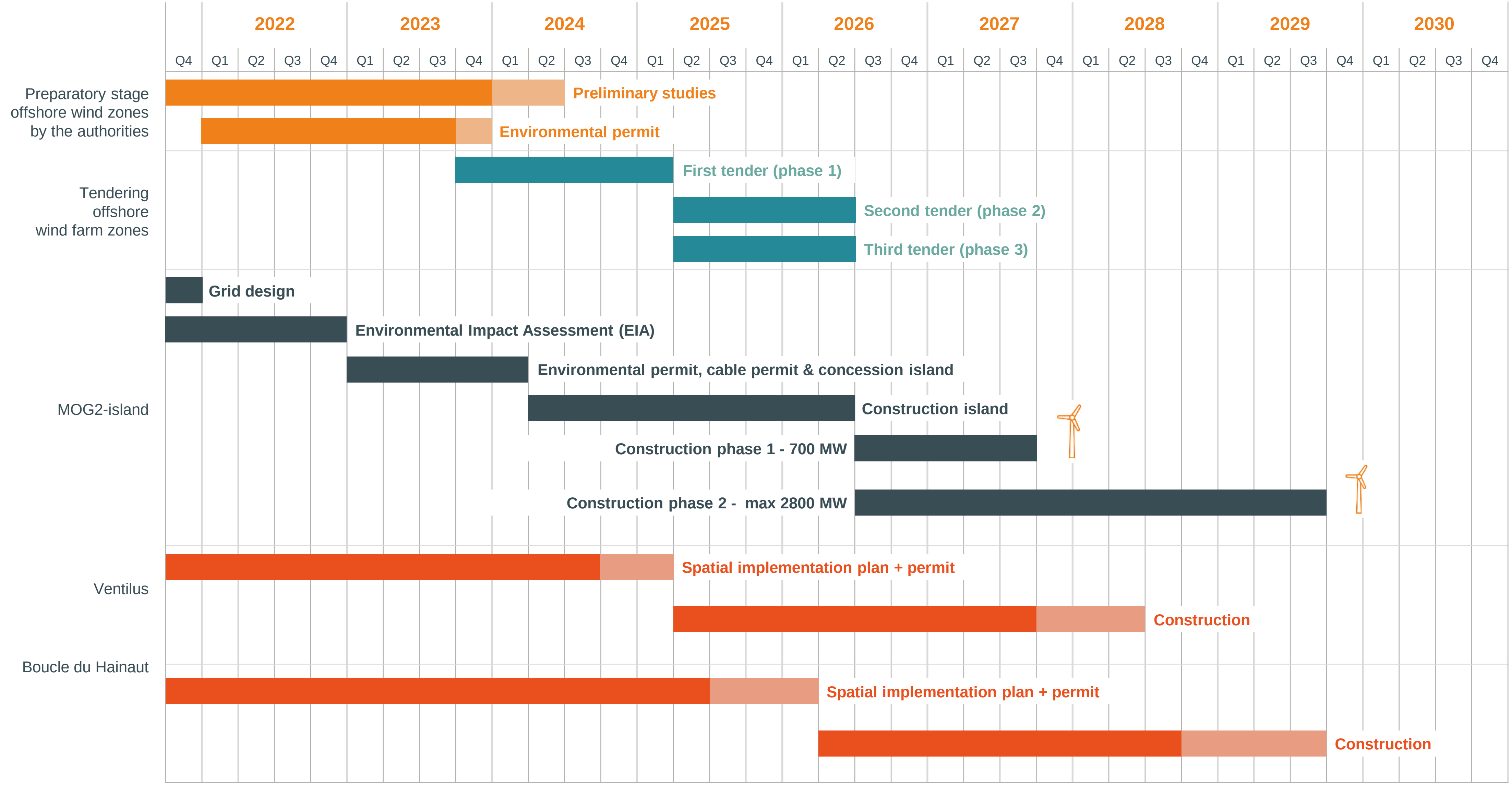
- Grid connection for 3,15 to 3,5 GW of additional offshore wind farms in the Belgian North Sea
- Connection point for future offshore interconnections

Main objective: maximise integration of renewables into the Belgian electricity system

Island project to be validated by ministerial decree**.**

The Energy Island Timeline

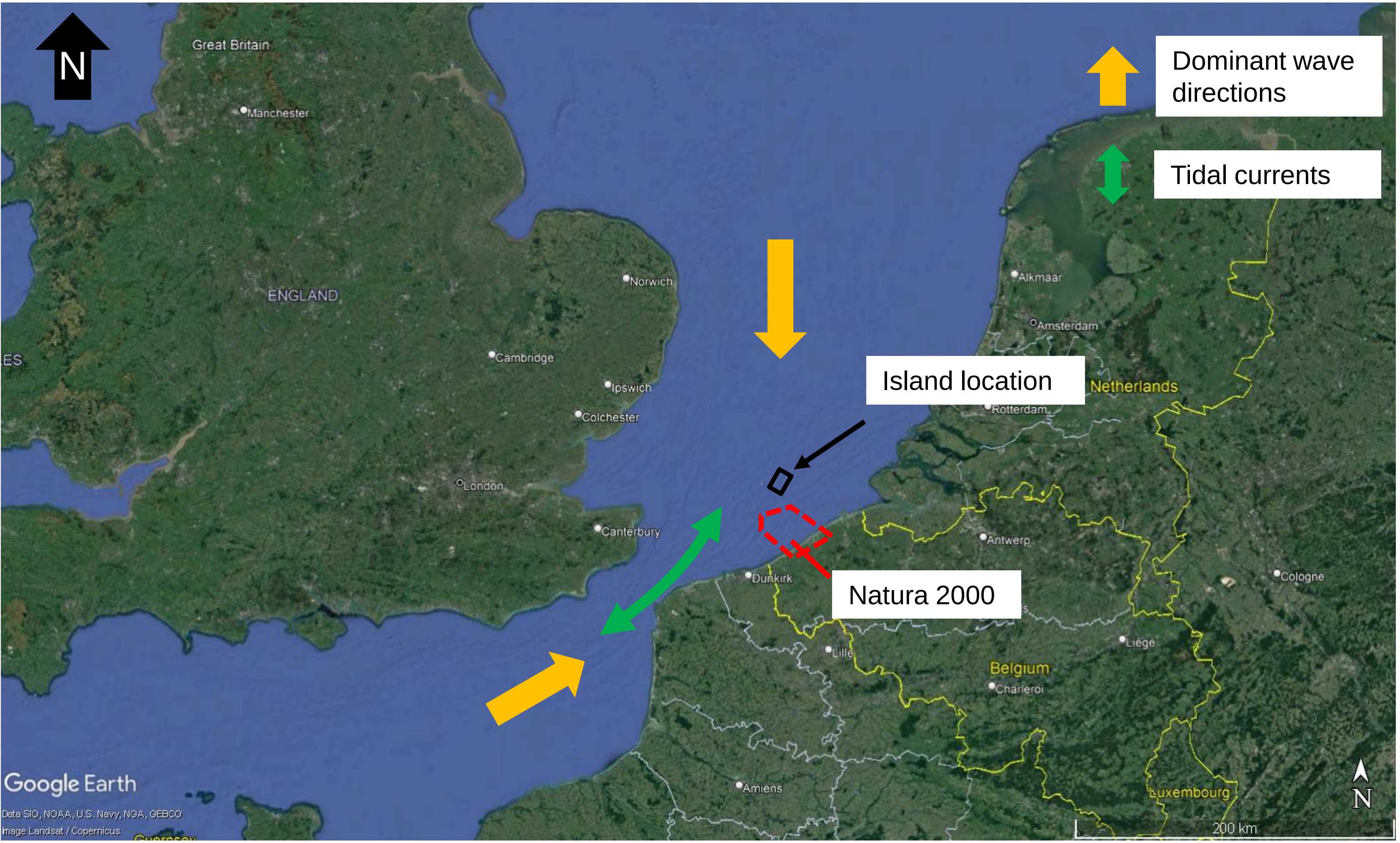
Official timing as communicated on administration website



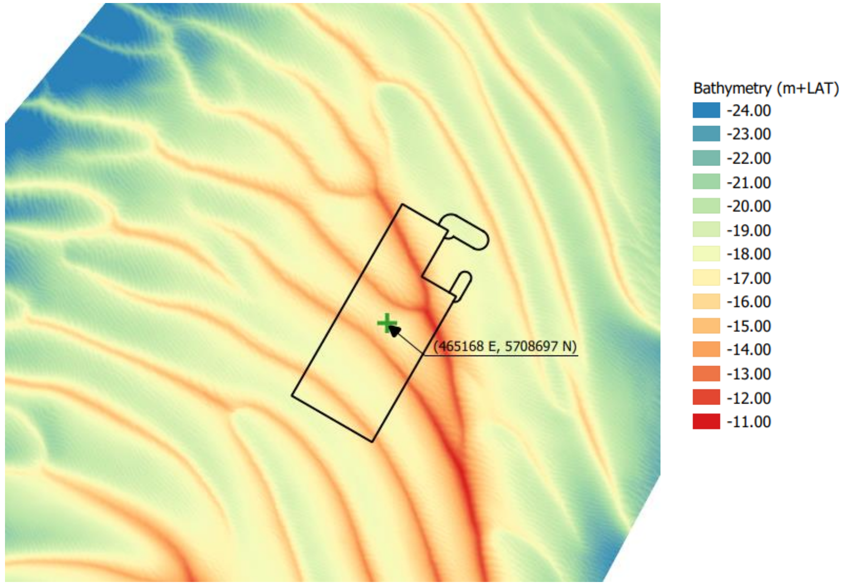
Island concept

Tom Trappeniers
Davy Verwilghen

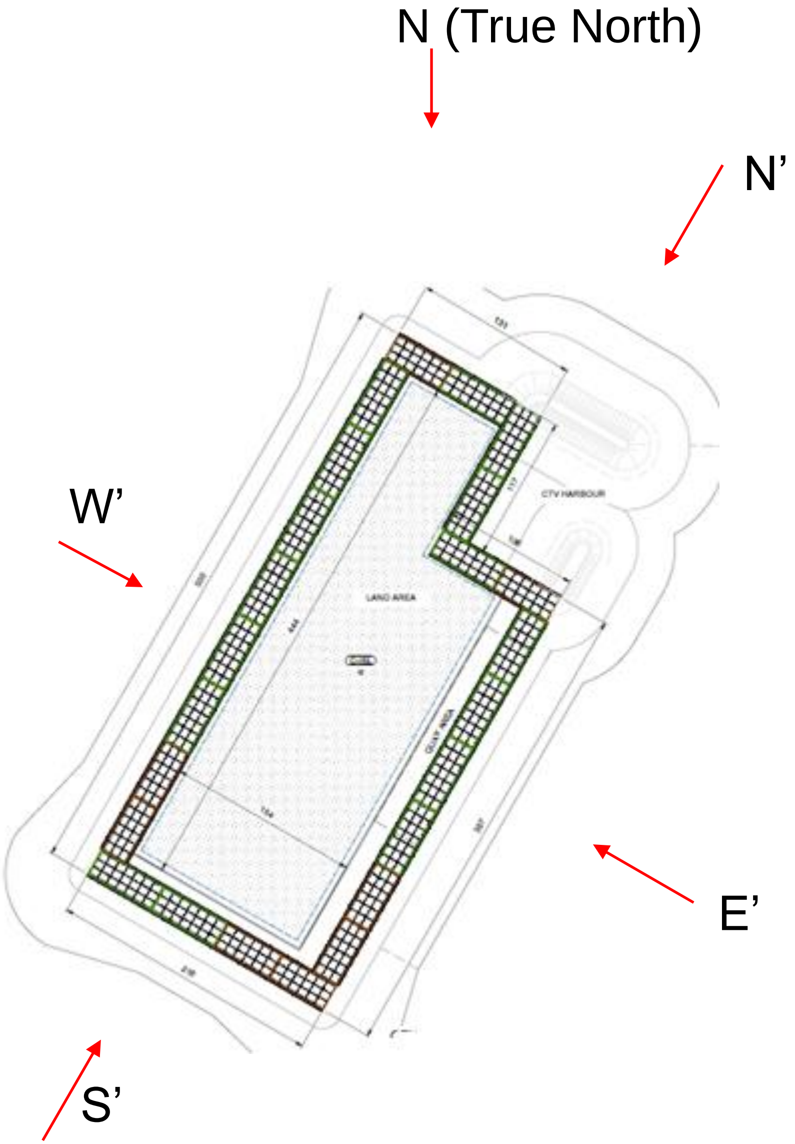
Island location and relevant conditions



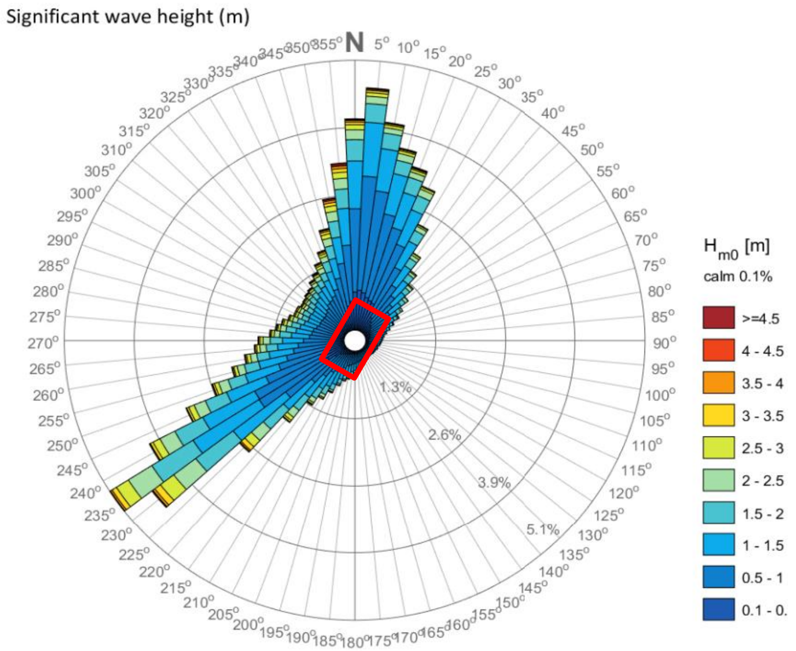
- Island located in Princess Elisabeth zone
- Island location subject to EIA



Island orientation

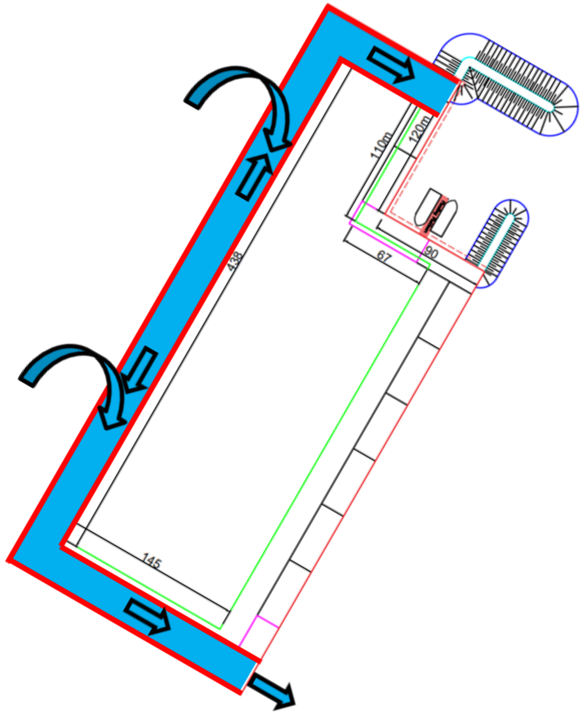


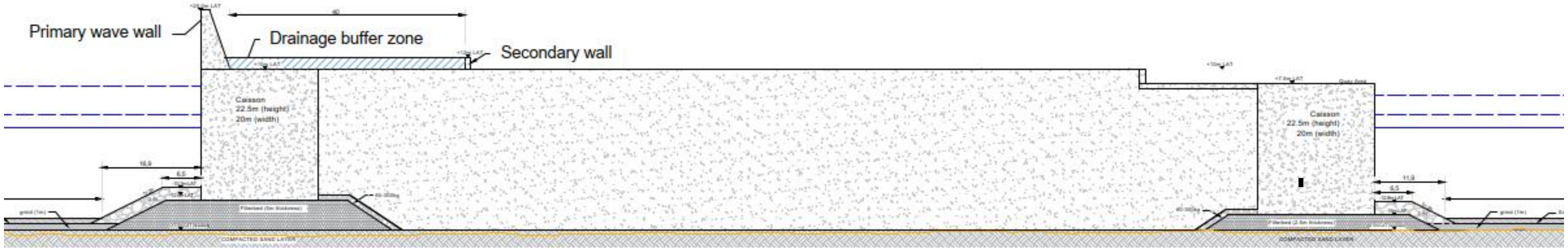
- The island has an orientation of ~30° in line with the tidal current flows to minimize environmental impact;
- Due to its sheltered location the Quay area and CTV port entrance are located on the Eastern side of the Island



Design concept / Rationale

- Caisson structure
- 3 sides ‘exposed’ (N, S, W) with high Primary wave wall to limit overtopping;
- Buffer zone behind Wave Walls to catch and drain overtopping water towards the Eastern (sheltered) side of the Island. This buffer zone shall be used for logistics and or cable routing
- Secondary wave wall of ~2m to prevent / minimize flooding of the ‘net useful area’ where the Grid Infrastructure is located.
- Sheltered Eastern side does not require an outer wave wall. Due to the sheltered location the Quay and entrance to the CTV port are located here





Island Design: potential layout

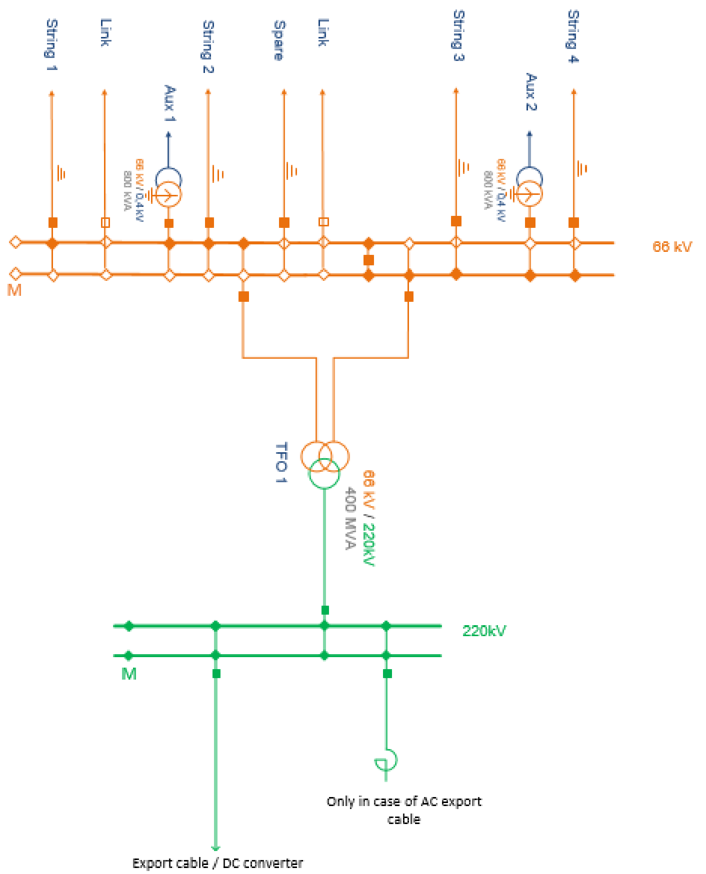
Grid design

Tom Trappeniers
Davy Verwilghen

Grid design

- **10 blocks of 350MW**
  - 1 transformer
  - 1 GIS cabine 66kV
- **Array cables:**
  - 66kV
  - 90MW/string
- **1 spare bay per 350MW**
- **1 export cable 220kV/ HVDC**
  - 1 shunt reactor per AC export cables

350MW building block



Impact of 132kV array cables

elia | Elia Group

- Turbines 14-18MW expected (2027 – 2030) *(= 10-13 turbines/string @ 132kV)*
- Turbine manufacturers not (yet) working on design 132kV*
- MVar compensation possible, but challenging (Q ~ U^2)

- Reduced array cable length
- Reduced # array cable landfalls on island
- Increased supply cost
- More power loss per outage (+/-90MW ->180MW)

- Impact on building size limited *(larger but fewer equipment)*
- AUX TFO challenging

- To restart: grid design, grid studies, conceptual design modules, tender prep.
- Project delay 10-12months

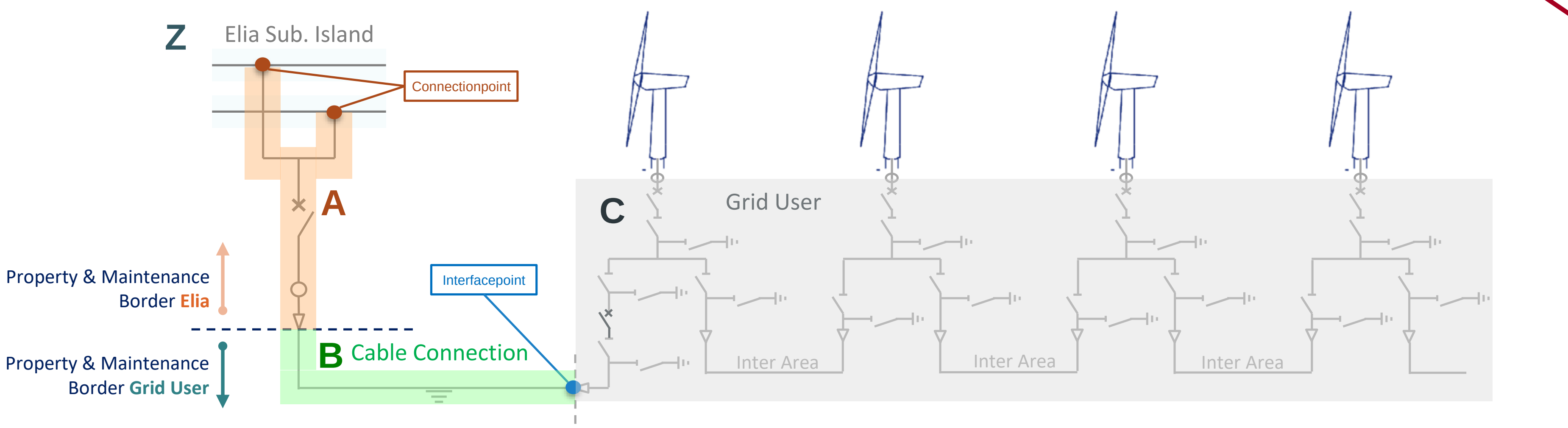
66kV chosen

* Assumption based on market survey performed in 2022 by 4COffshore

Interface point & protection philosophy

Damien Rietjens
Davy Verwilghen

Interfaces



Connectionpoint

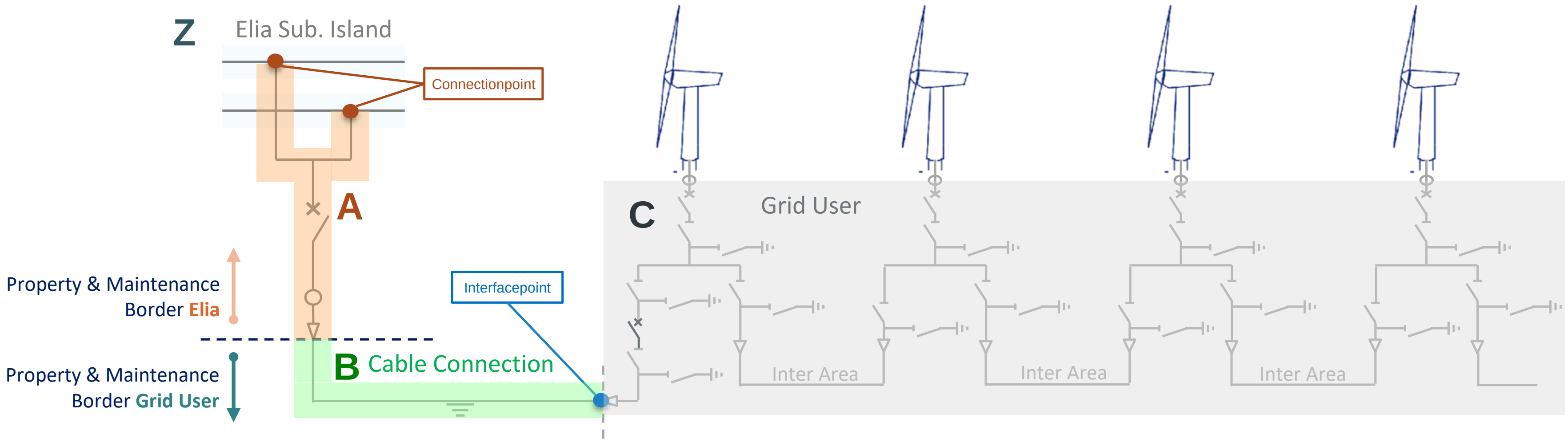
The **Connection Point** is the point where the Grid User is connected to the grid. It is usually located at the connection terminals of the busbar where the Grid User is connected to the grid (via its first connection field)

Interfacepoint

The **Interface Point** : the physical location and the voltage level of the point where a Grid User's installations are connected to the connection installations. This point is located on the Grid User's site and in any case after the first connection field from the grid on the Grid User's side;

- **Z** — **Part Z** : All Installation/equipment **belonging to the Grid**
- **A** — **Part A :** All **High Voltage (HV) equipment** of the Grid belonging to the customer's connection. These **are fully allocated to the customer**.
- **B** — **Part B : The connection** between the connection field and the Grid User's installations
- **C** — **Part C :** **HV equipment** from the **Grid User**

Interfaces



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A **Part A :** All **High Voltage (HV) equipment** of the Grid belonging to the customer's connection. These **are fully allocated to the customer**.

B **Part B : The connection** between the connection field and the Grid User's installations

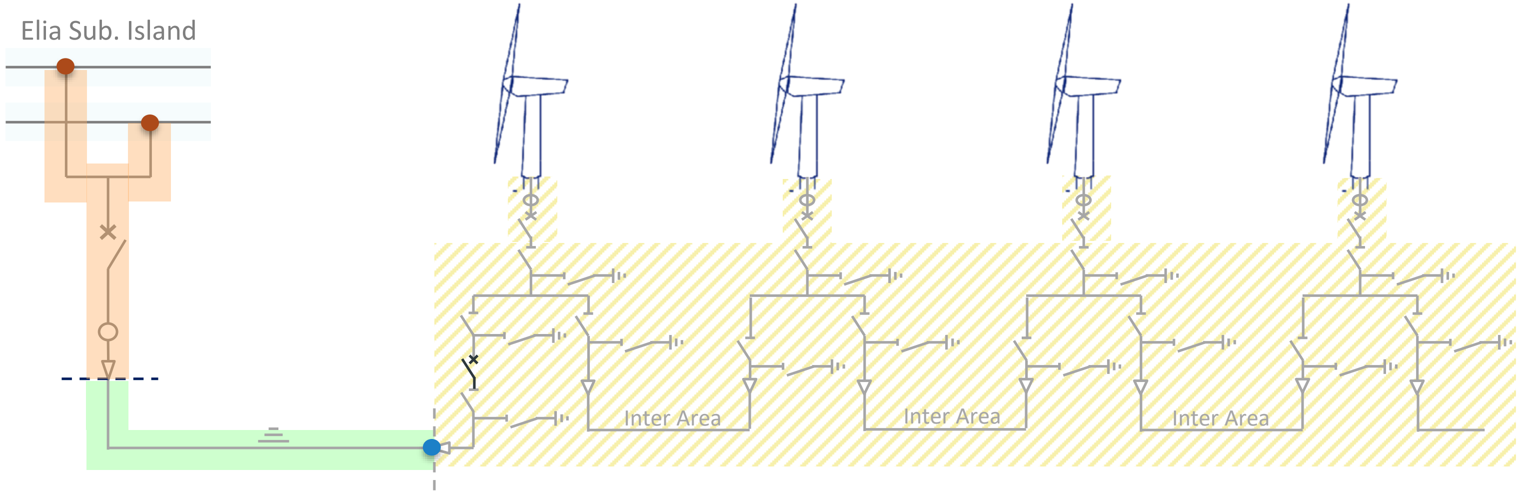
C **Part C :** **HV equipment** from the **Grid User**

Operations

Elia Operates first connection field

Grid User fully and independently operates the entire string as of the first wind turbine

In order to be fully independent a circuit breaker is placed in the first wind turbine

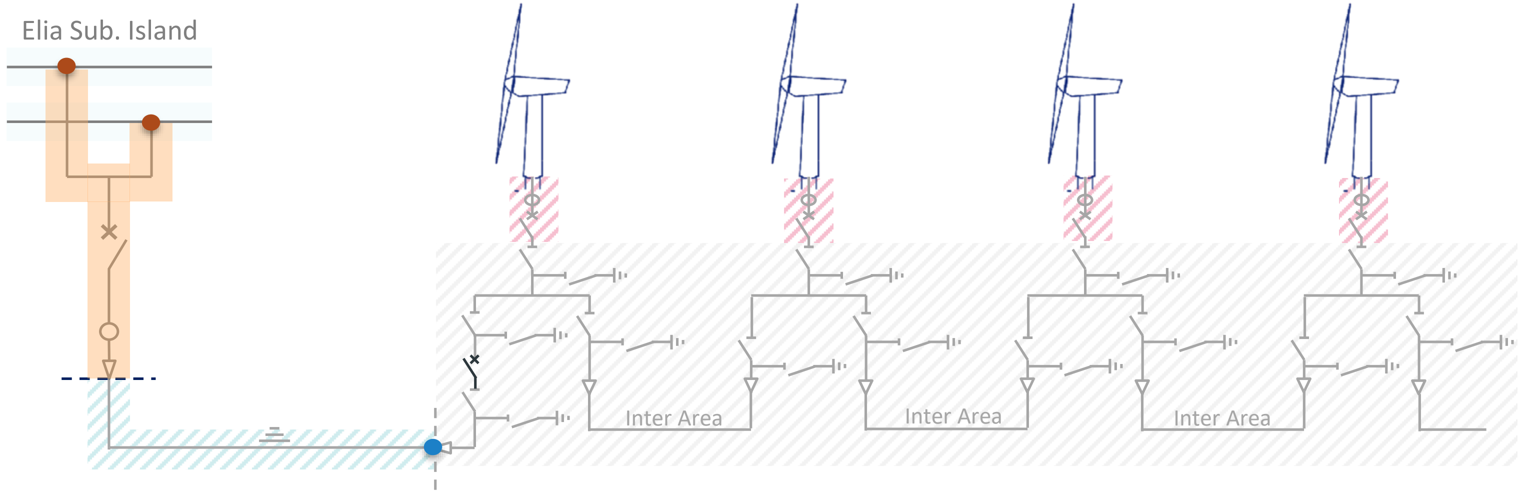


Protections

Elia protects and defines parameters for the first connection between the first connection field and the first Wind Turbine

Elia and the Grid User jointly define the parameters of the part of the string behind the first cable connection at the first turbine

Grid User protects each wind turbine by installing own local protection that trips the circuit breaker (settings will also be shared and aligned with Elia)



SLD for discussion (not exhaustive)

Operations

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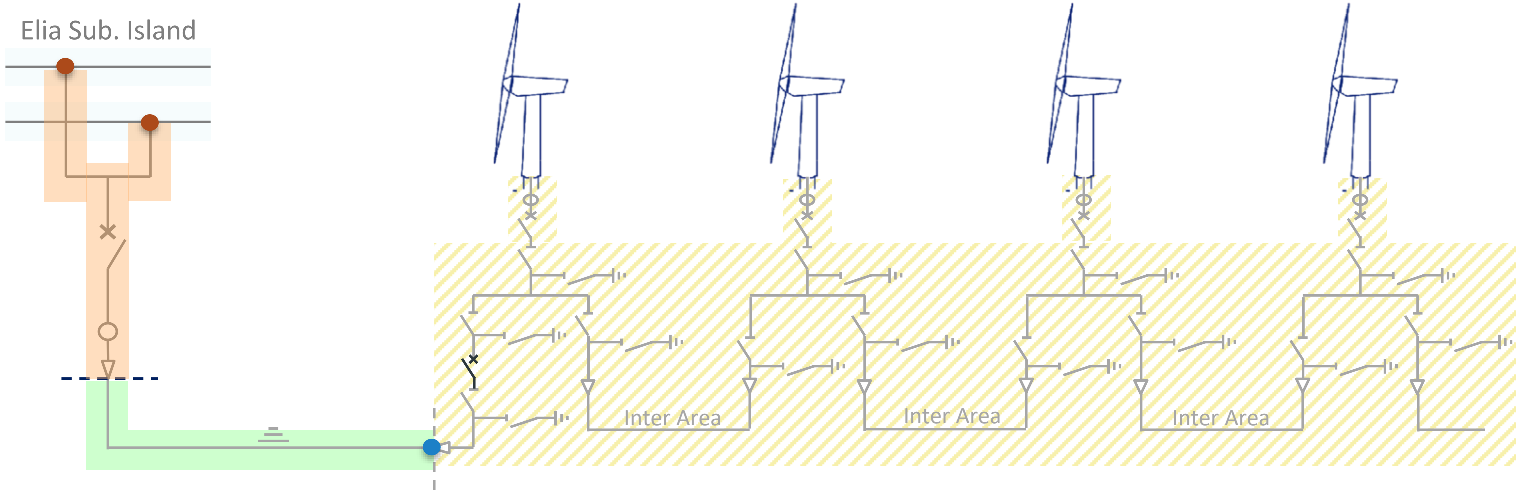

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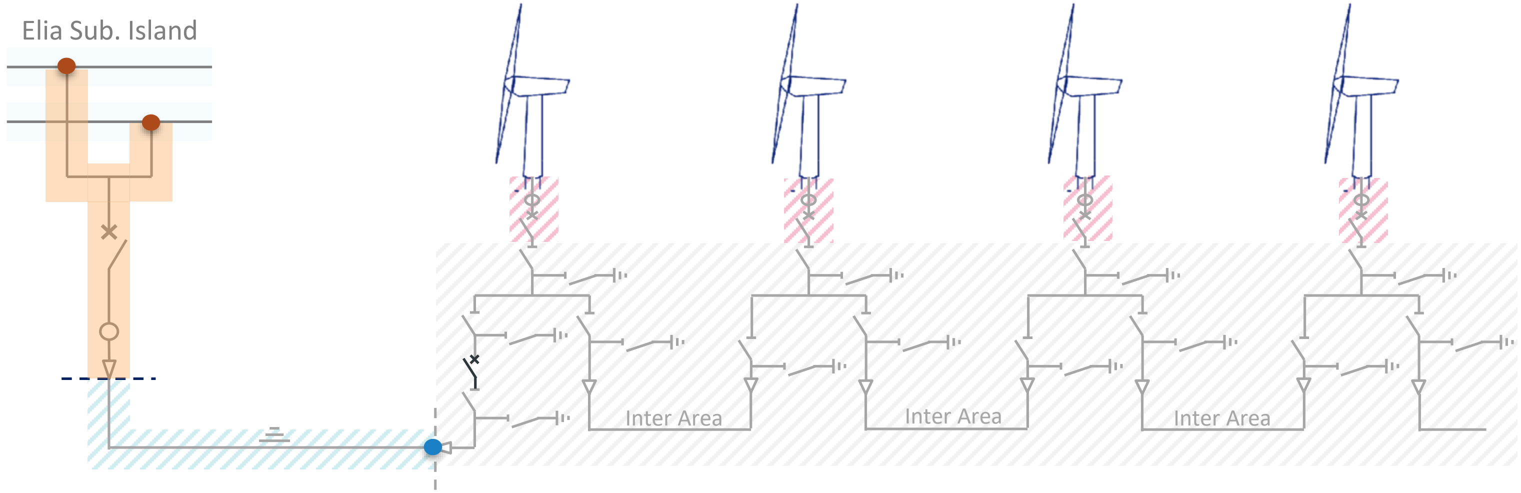


Protection 66kV feeders

- 66 kV feeders are protected with P1 and P2
  - Two distance protections
- Protection settings and coordination : shared responsibility between customer and Elia
  - Forward zones (direction cable): to be agreed between customer and Elia
  - Backward zone (direction busbar): to be decided by Elia
  - Cable overload protection: to be decided by customer
- One bay controller with built-in measurement convertor
- Second measurement convertor with 4… 20 mA output to customer (via interface cubicle)
  - Redundancy needed ?

Windfarm Interface and communication cubicles

Tom Trappeniers
Davy Verwilghen

Windfarm Interface and communication cubicles 1/2

1 room per windfarm operator.

- Interface cubicle WPO – TSO: 1 or 2 cubicles?
  - Hardwire vs protocol interface to be investigated
- Windpark control cubicles: 2-3?
- Telecom cubicles: 1or 2?
- DTS?: 2?
- Metering: tbd
- Desk + cupboard for schematics? Other?

➔ **any thoughts?**

Windfarm Interface and communication cubicles 2/2

Elia will provide « dark » fibers in the export cables

- # of fibers to be determined: 24?

Elia will provide AUX power supply

- 2x 110DC
- 1x 230Vac?

➔any thoughts?

Open questions

Tom Trappeniers
Davy Verwilghen

Summary of open questions

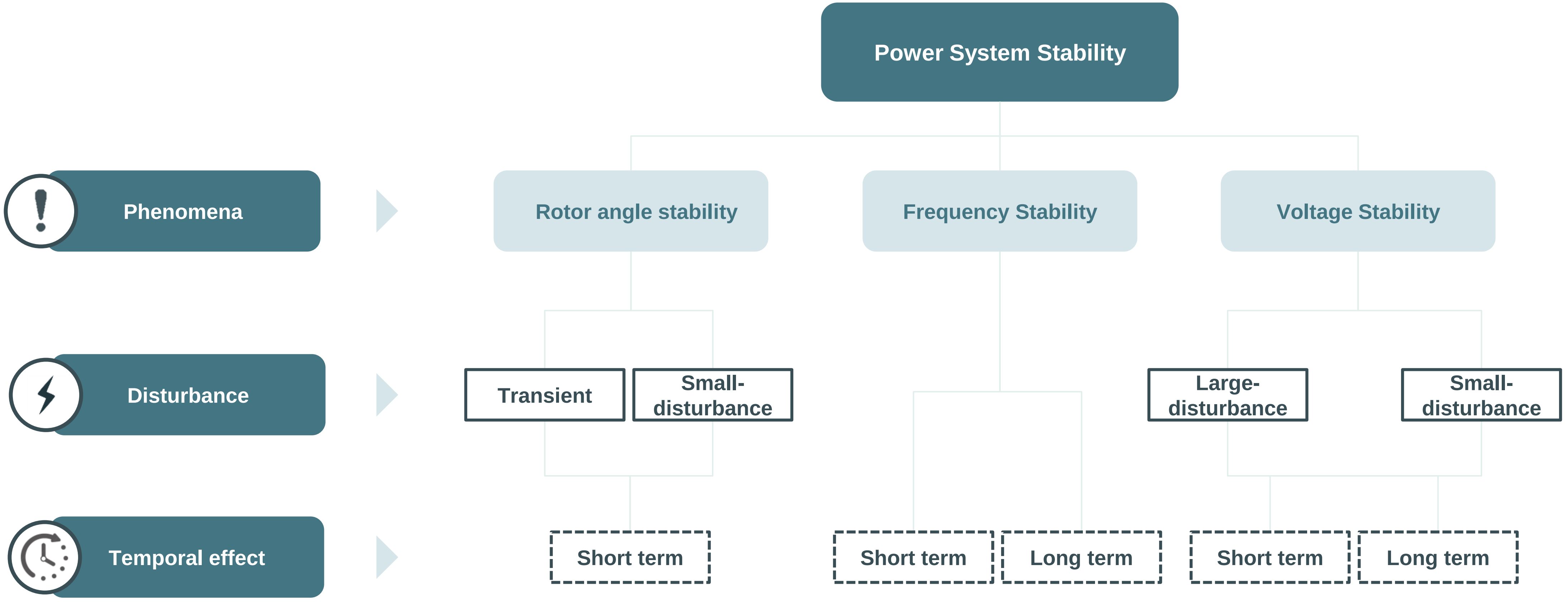
- Required space in windfarm operator room
- # of fibers per windfarm
- Requirements 110Vdc, 230Vac,…
- Would you consider HV tests on the 66kV cables?

Dynamic & Harmonic

Generalities

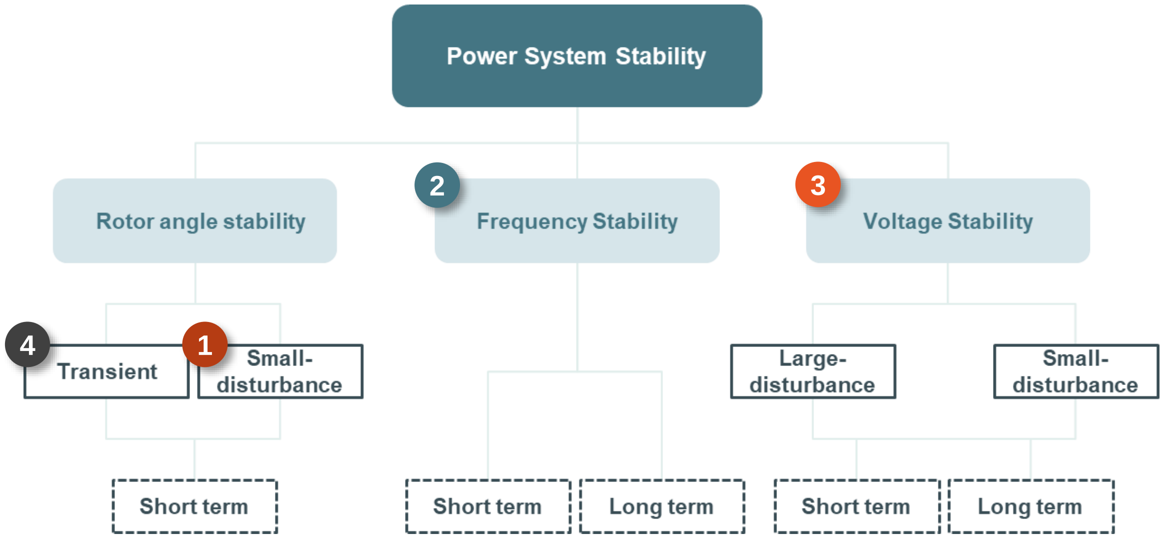
Olivier Bronckart

Power system stability and phenomena are not new and already faced and mastered on existing AC extra high voltage grid since several decades

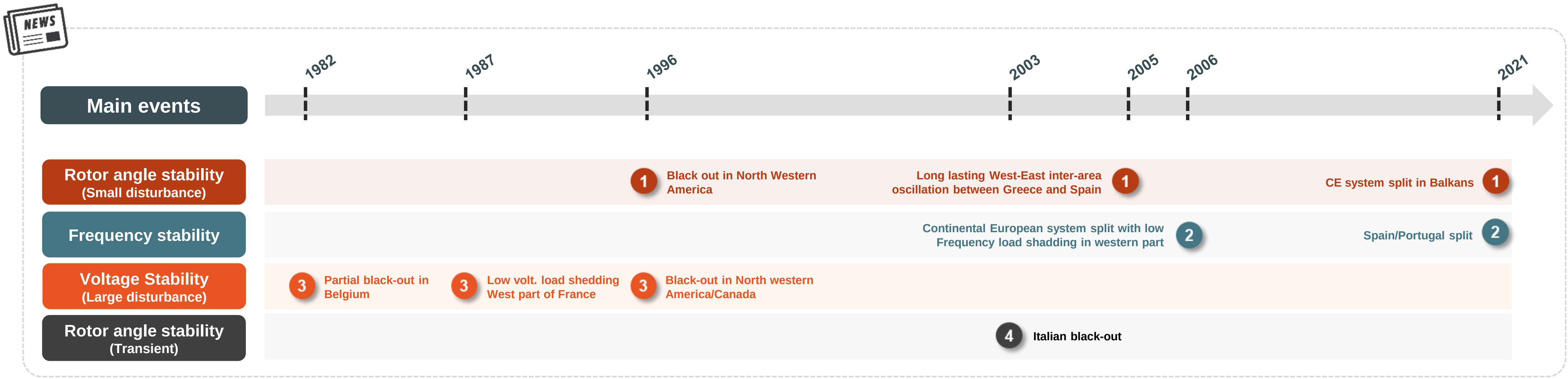


A **system is stable if under all conditions** (following any type of normal or exceptional contingency, switching event or load and generation variation) **during the transition between 2 normal operational** security steady states, power system dynamic and harmonic stability is **ensured**. In other words, all phenomena listed here are understood and managed.

Several impacts of these phenomena were already observed in the past and require development of solutions to limit the impact



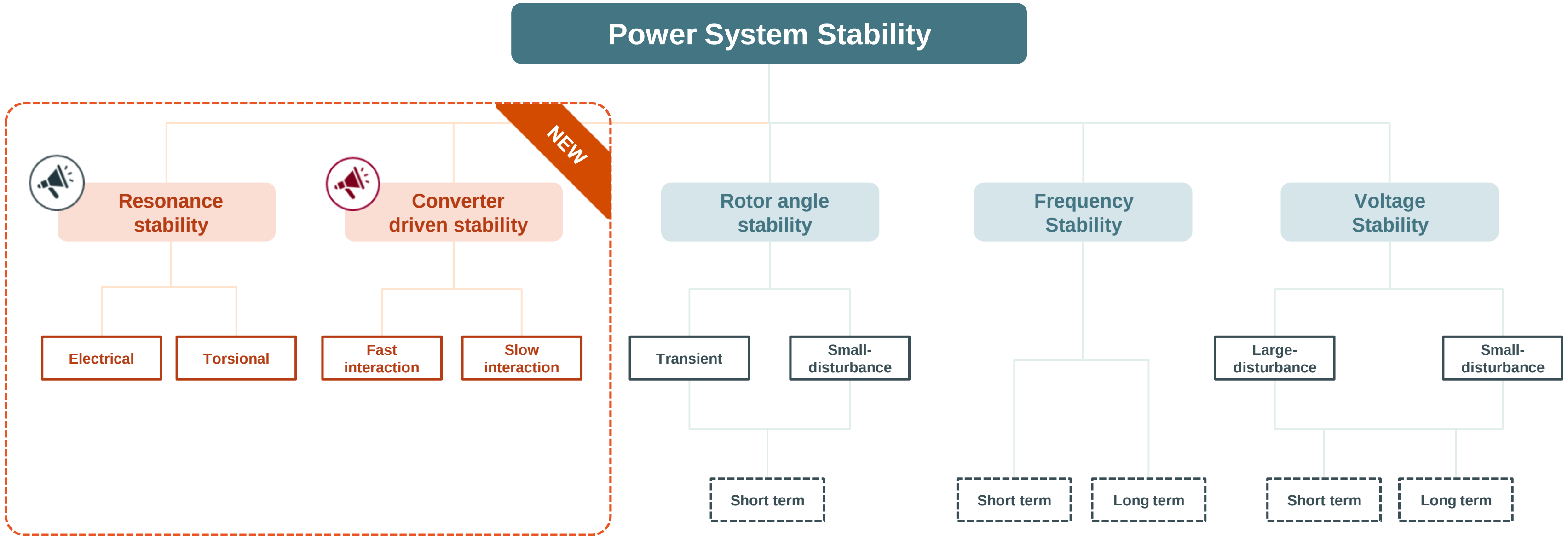
Examples of some events observed in the past



Recent and future trends of the power system leads to new phenomena

Recent and new trends

- Increasing & accelerating RES ambition
- Development of offshore grid
- Increase of power electronic converter & interface devices
- Nuclear phase-out
- Increasing exchanges over long distances



Several consequences of these new phenomena due to interactions with power electronics were observed abroad

Event - Asset damage in Germany

- Offshore HVDC damages due to harmonic interaction
- Solved by adding filters
- HVDC out of service for some time

→ **large non-injected power**

→ **additional cost for system**

Event - System security issue

- Disconnection of injectors and cascading
- Local/global black-out
- Image/regulatory

→ **additional important cost for system**

(Example unavailability of the MOG (1GW) has a cost 0,5M€ -1,5M€/day)

Power electronics vs “rest of the system” will require solutions to keep stability under control to guarantee the security of the grid

(MT)HVDCs (& IBRs)

- New technology
- Intellectual property issues on behavior / modeling
- Control-driven process (non standard and “hidden”)
- Mix of fast/slow phenomena
- May go beyond the limits of the current simulation software (?)

Rest of the system

- “Old technology”= well understood
- Open information as technology is mature
- Physic – driven process “Slower phenomena”
- Standard models
- Analysis techniques well established for classical problems

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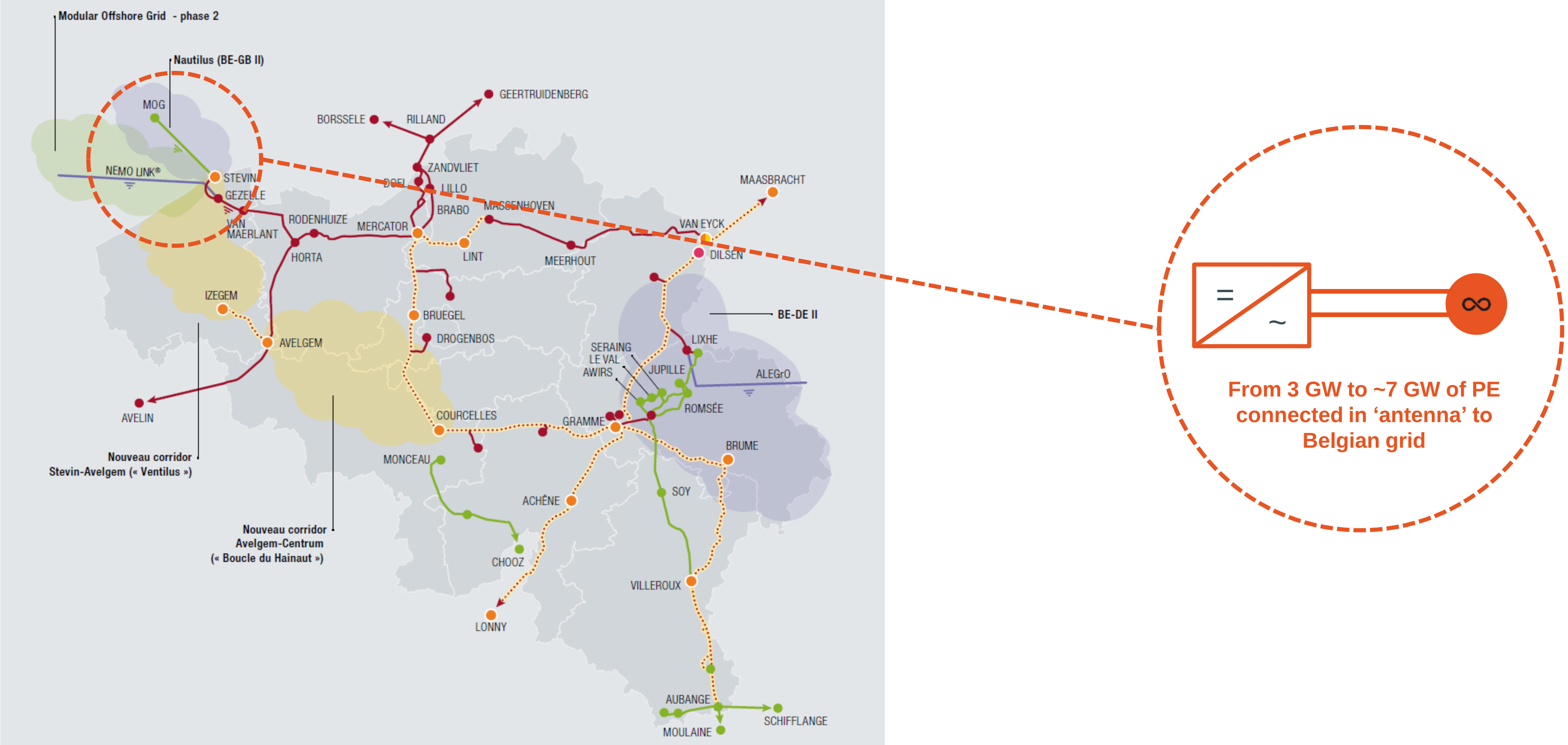
- To avoid that power system stability becomes a bottle neck we must **ensure that under all conditions**, transient, (dynamic and harmonic) stability remains ensured within normal operating conditions
- Since some of these challenges are unprecedented in the world, it will be required to **facilitate** and increase the speed of **knowledge development** in this area of expertise (incl. R&D)
- The state of the art **processes** and **tools** must be implemented to allow efficient screening and assessment of these phenomena, starting from long term development until real-time
- If and **when stability risks** are detected, **efficient solutions** must be designed and implemented

MOG 2 case

Olivier Bronckart

EHV evolution of the Belgian Coastal area for 2030



High concentration of Power Electronics in the coastal area, where grid condition in N are weak, and even weaker in case of corridor trip for the stability and risk of interaction between the controllers

Several challenges are foreseen with the integration of 7 GW of power electronics in BE coastal zone

1 **Challenge I**

High concentration of PEs connected in one single point CE synchronous area and leads to new power system stability phenomena

2 **Challenge II**

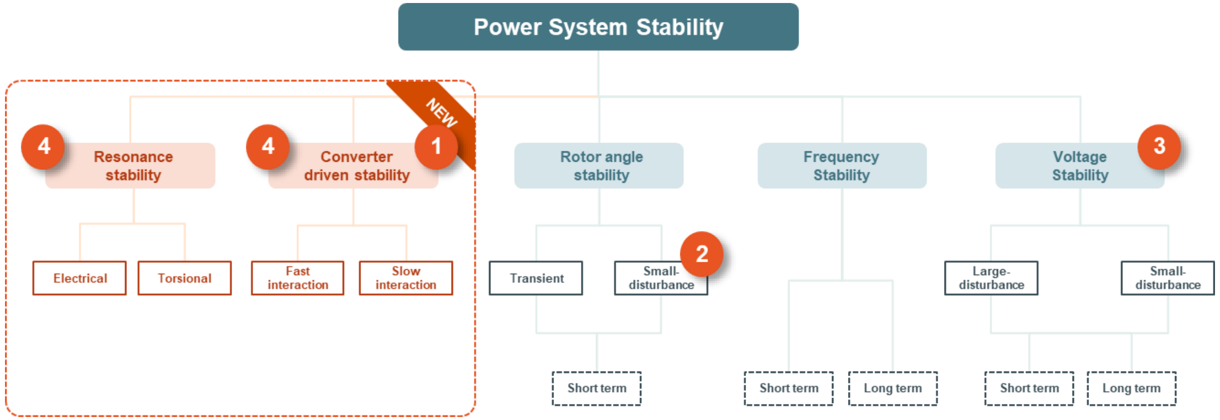
Forced active power oscillations observed on MOG I and to be anticipated on MOG 2

3 **Challenge III**

Maximum transmissible power issue in N-2 will require onshore grid solution

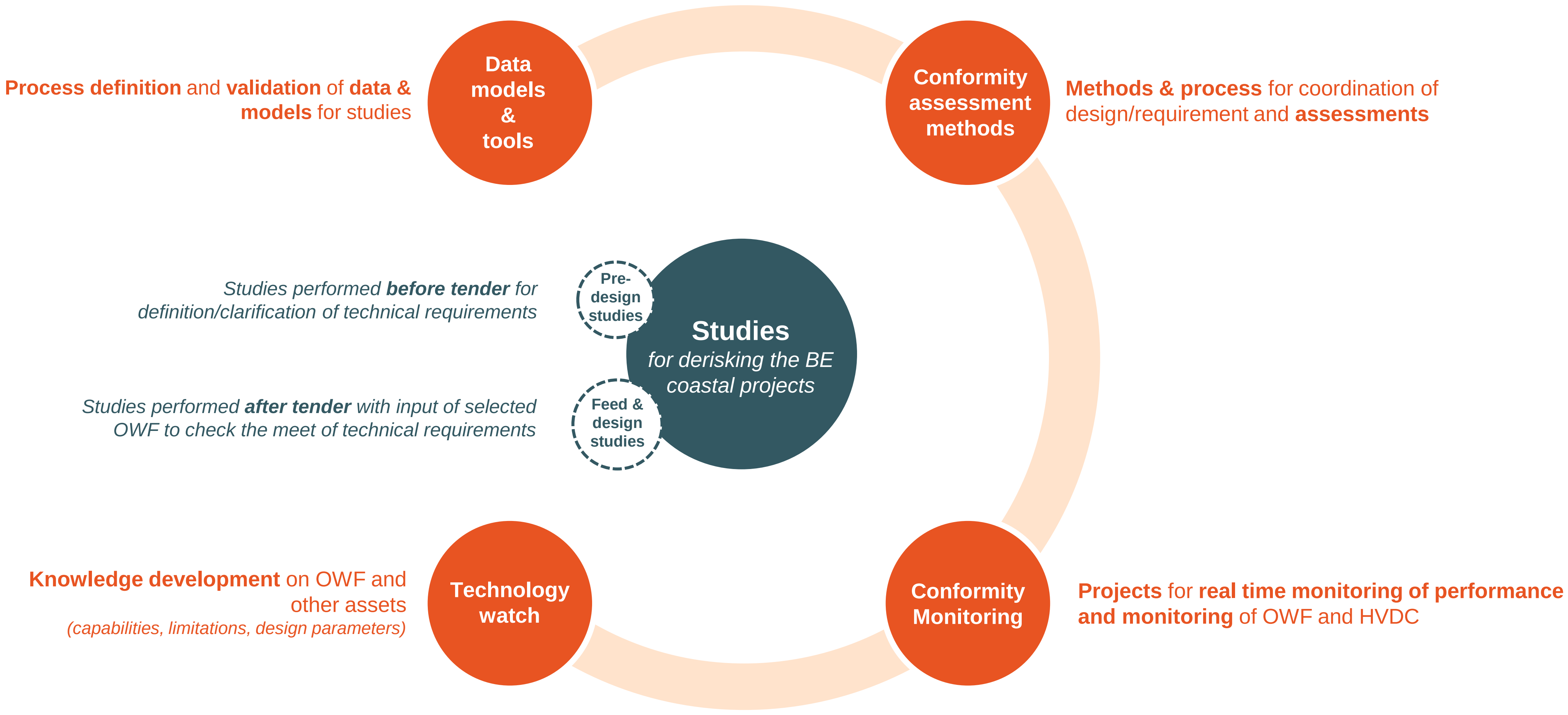
4 **Challenge IV**

Larger multi-vendor and will require process clarification for data and model process coordination



- **Solutions shall be found** to keep stability under control **to guarantee the security of the grid** and **avoid consequences** for the Belgian and Central Europe grid
- ELIA shall investigate and propose **solutions** considering improvements in both **system design** and **grid connection requirements**

Several activities and studies are required for derisking the Belgium coastal projects from pre-design till real time operation



4 main clarifications will be potentially defined in the technical requirement for 1st tendering of MOG 2 OWF

1. **Forced oscillations:** this phenomena must not lead to critical consequences for BE/EU system

2. **Process for data sharing & model validation:** need for process definition on data and model sharing from asset owner to perform conformity study

3. **Coordination of design study:** need for coordinated simulations/studies to perform conformity study

4. **Voltage control:** adjustement of voltage and MVar capabilities (owner of step-up transformer shift from OWFs (MOG 1) to Elia for MOG 2)

The output of pre-design studies might require additional adaptations

Forced oscillations

Fortunato Villella

| Elia Group

4 main clarifications will be potentially defined in the technical requirement for 1st tendering of MOG 2 OWF

1. **Forced oscillations:** this phenomena must not lead to critical consequences for BE/EU system — **Introduction today**

2. **Process for data sharing & model validation:** need for process definition on data and model sharing from asset owner to perform conformity study

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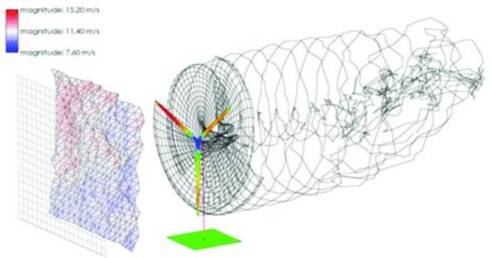
The output of pre-design studies might require additional adaptations

Forced oscillation is a mechanical phenomena that can impact the electrical system

External phenomena ▶ **Mechanical consequences** ▶ **System consequences**

External phenomena

Aerodynamical perturbations (non constant wind)



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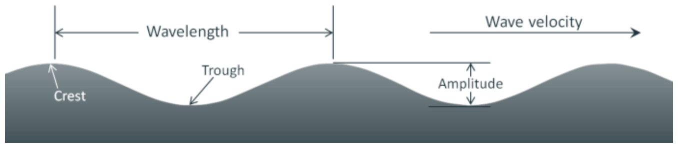
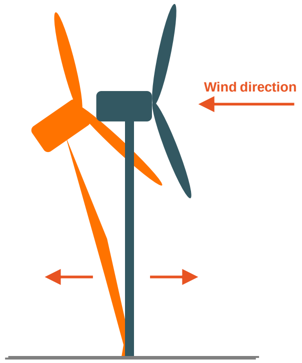
Sea waves on wind farm structure

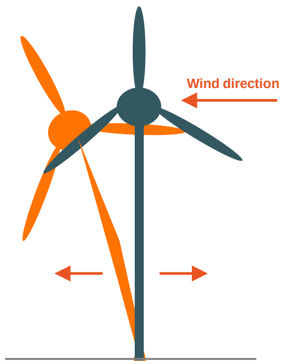


Mechanical consequences

Vibration/movement impacts fatigue on the mechanical structures



Tower fore-aft



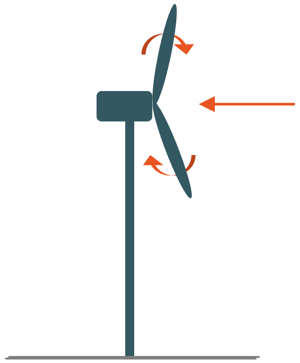
Tower side-to-side

Compensated automatically by the rotation of the masses ✔

May require additional system ⚠

System consequences

May lead to system stability issues that can trigger protection and disconnect OWF



Tower fore-aft

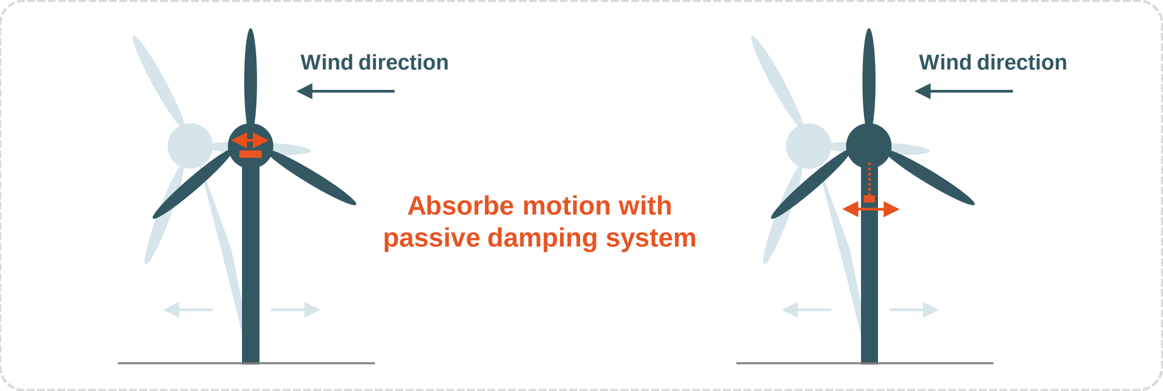
2 possible solutions on OWF directly

- **Passive damping**
- **Active damping** (Side-to-Side)

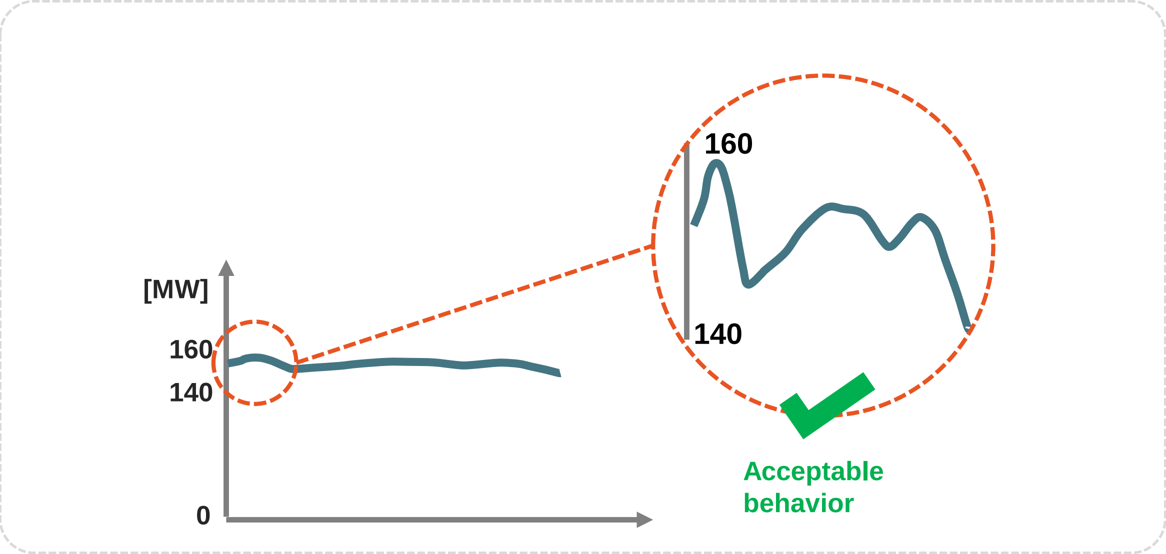
See next slide

Active damping impact and worsens interarea oscillations

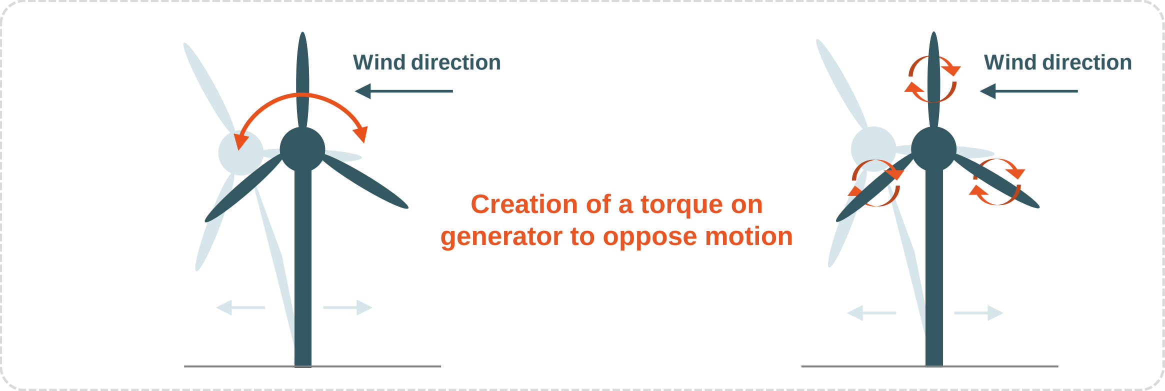
Passive damping



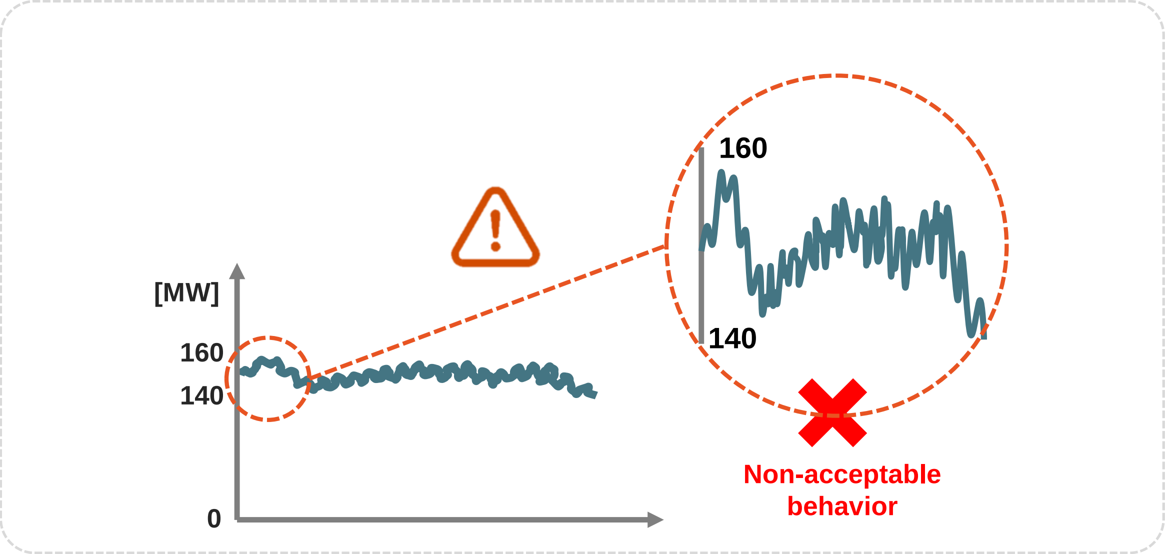
Passive damping has **no impact** on electrical system **but more expensive** for constructor (more weight)



Active damping (Side-to-Side)



Electrical forced oscillation at **critical EU frequency** [0.1 – 0.3 Hz] **and** can excite **interarea oscillation**

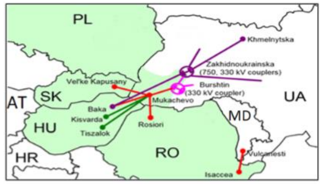


Interarea oscillations can lead to critical consequences for EU system

Interarea oscillation phenomena will increase through the years with system evolution (increased exchanges, reduced inertia, integration of renewables…) and an increase of probability of occurrence will happen.

Several consequences of interarea oscillations

1. **Frequency/Voltage collapse**
   Triggering protection devices on several lines
2. **Cascading and system split**
   High risk of large blackout/brownout



Spectrum UA-Donbaska

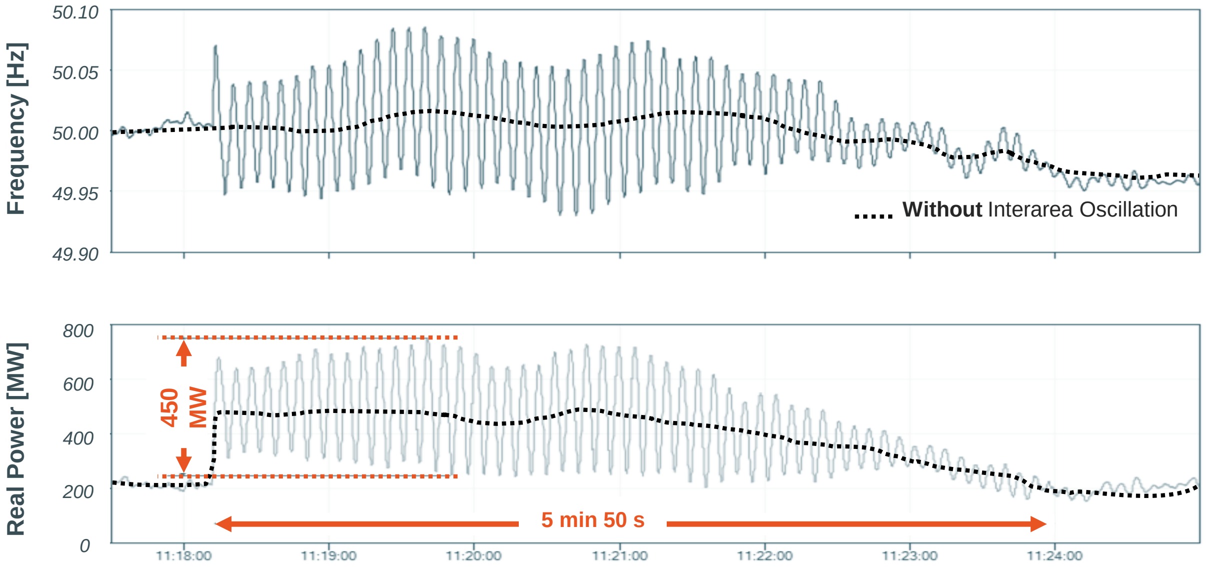
Limiting interarea oscillations can be cost impacting

e.g. Some EU countries have to reduce their export (with costly international redispatch) to limit the interarea oscillations

No mitigation action is known today to forced oscillation

other than **disconnect the parks as they oscillate at all levels of power injection**

Illustration of interarea oscillation effect on frequency and real power (past event)



- All the **major vendors** have side to side damping function ➔ **Large** collective overall **impact** expected from **northsea (FR-BE-NL-DE-DK) wind parks**
- **Experiences in ENTSOE** and experience in other countries (**US**) show that **forced oscillations negatively impact interarea modes**
- **Phenomenon** is **to be** avoided by proper design of wind farms (problem to be solved at the source) ➔ **No forced oscillation allowed**

Balancing and system integration

Agenda

1. **General status of the study and planning (5')**

2. **Projections of the offshore generation profiles (45')**

Presented by external consultant Matti Koivisto of the Technical University of Denmark to which the simulation of future offshore generation profiles has been assigned to.

3. **Methodology for the impact assessment on balancing and system integration during (20')**
    1. normal conditions : impact on reserve capacity needs
    2. exceptional conditions : impact of storms and ramps on system operation

General status of the study and planning

Kristof De Vos

Re-cap : scope of the update of the system integration study

Projections of offshore generation profiles (DTU)

- ***Scope on :***

Update simulation of future offshore generation profiles and corresponding prediction errors

  - *During normal conditions*
  - *During extreme wind power conditions (storms and ramps)*

- ***Focus on :***

I. *Increase installed capacity projections up to 5.8 GW*

II. *Update of the technology assumptions where relevant*

Impact assessment of exceptional conditions and need for mitigation measures

- ***Scope on :***

Update of real-time system simulations

Confirm or amend proposed mitigation measures impacting the Tender.

  - *High wind speed tech.*
  - *Preventive curtailment*
  - *Ramp rate limitations*
  - *Cut-in coordination*

- ***Focus on :***

I. *Investigate how the expected impact on the system impacted by increasing the capacity to 5.8 GW*

II. *Investigate if the proposed mitigation measures still adequate in a 5.8 GW offshore context*

III. *Investigate impact of evolutions such as offshore bidding zones or consumer centricity*

Impact on flexibility and reserve needs

- ***Scope on :***

Update on Elia's expectations on future reserve needs and procurements

Less relevant for the tender but large impact on real-time system operation and costs

Flexibility study is proposed to be kept outside the scope as the 5.8 GW was covered by high RES scenario.

- ***Focus on :***

I. *Analyze the effect of 5.8 GW offshore on the system's reserve needs*

II. *Analyze pre-conditions of the market to manage reserve needs and costs (consumer centricity)*

LFC block configuration

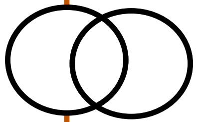
- ***Scope on :***

Assess the impact of an offshore bidding zone configuration on reserves, system operation and proposed mitigation measures

- ***Focus on :***

I. *Analyze the impact on LFC block structure and balancing market ?*

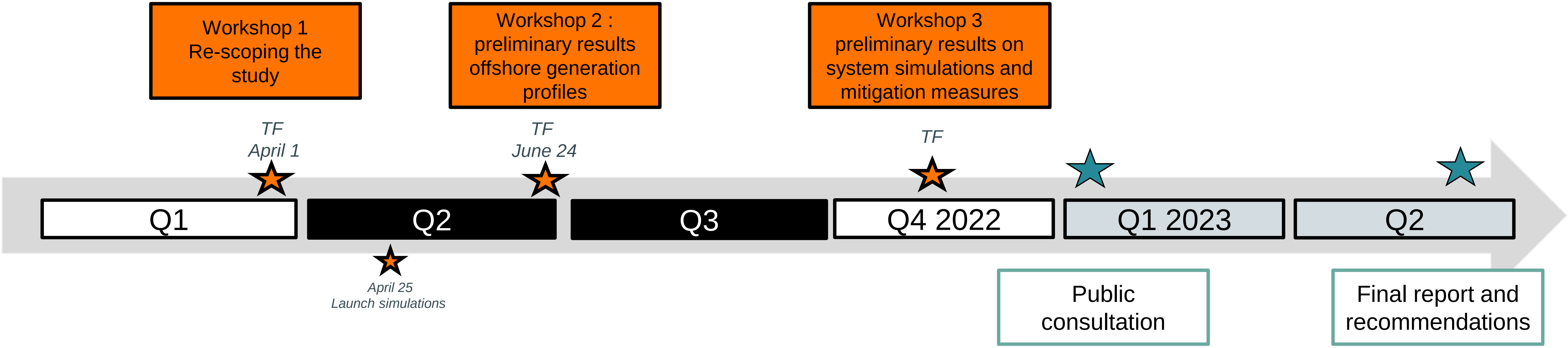
II. *Analyze the impact on reserve dimensioning, real-time system operations and recommended mitigations measures*



Market integration

FGOV – “De publicatie van de eerste oproep tot mededinging is voorzien in het vierde kwartaal van 2023”

Planning



- The planning of this study is retro-actively made to deliver our recommendations to the tender by 1.7.2023
- If due to new evolutions, the timing of this study is impacted, this will be discussed with the stakeholders

Projections of the offshore generation profiles

Presented by external consultant Matti Koivisto of the Technical University of Denmark to which the simulation of future offshore generation profiles has been assigned to.

Elia MOG 2: Wind simulations by DTU Wind and Energy Systems

2022 study update

Matti Koivisto (mkoi@dtu.dk)
DTU Wind and Energy Systems

24 June, 2022, online

Agenda

- The applied methodology

- Updates in the assumptions
- Updates in the modelling

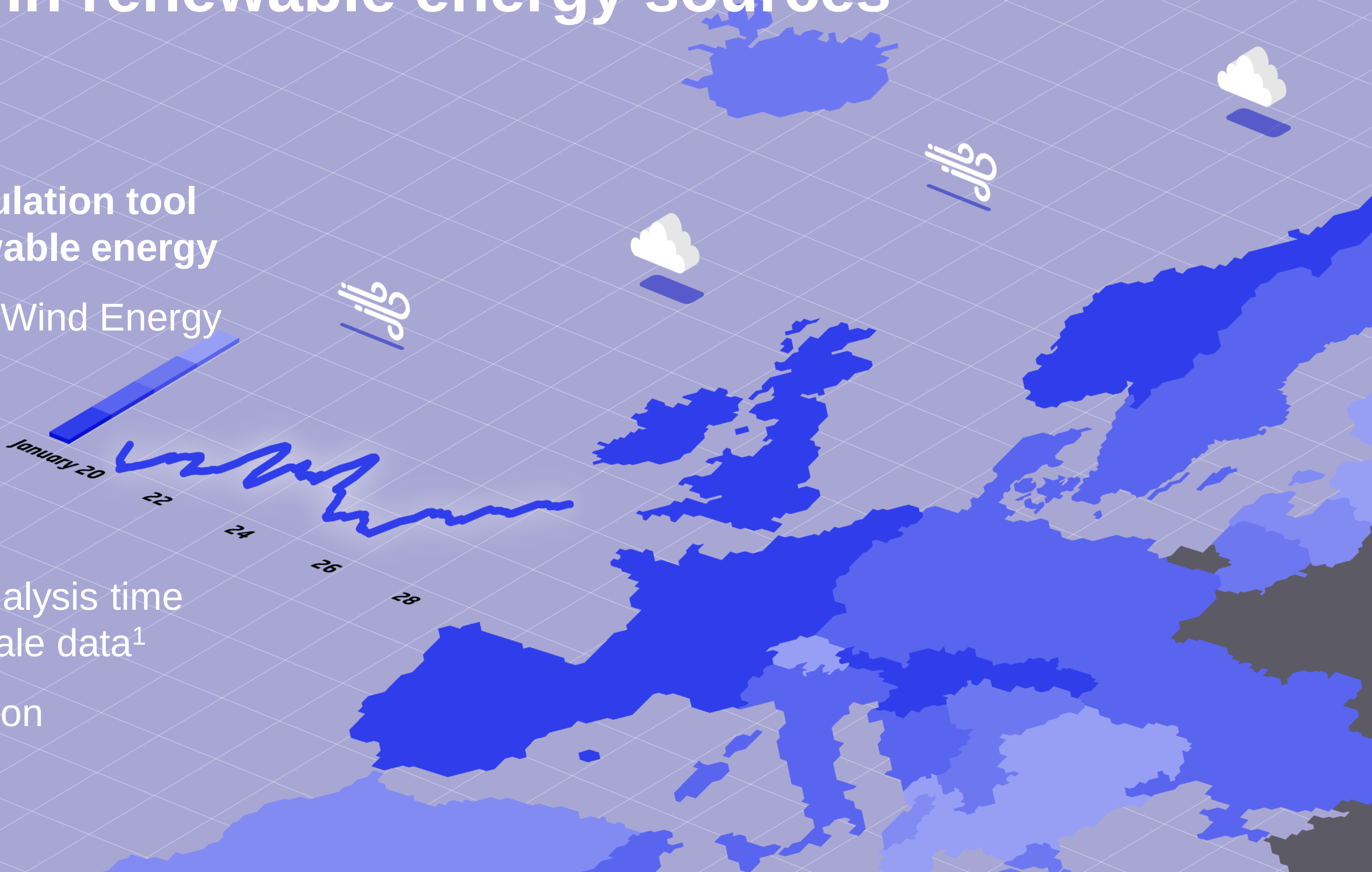
- Update of model validation

- Scenario results, with comparisons to the 2020 report

Methodology

Correlations in renewable energy sources (CorRES)

- **A time series simulation tool for variable renewable energy**
- Developed at DTU Wind Energy



- Globally using reanalysis time series and microscale data[1]
- Sub-hourly simulation capabilities[2,3]

[1]J. P. Murcia, et al., “Validation of European-scale simulated wind speed and wind generation time series”, *Applied Energy*, 2022 (https://doi.org/10.1016/j.apenergy.2021.117794)

[2]J. P. Murcia Leon, et al., “Power Fluctuations In High Installation Density Offshore Wind Fleets”, *Wind Energy Science*, 2021. (https://doi.org/10.5194/wes-6-461-2021)

[3]M. Koivisto, et al., “Combination of meteorological reanalysis data and stochastic simulation for modelling wind generation variability”, *Renewable Energy*, 2020 (https://doi.org/10.1016/j.renene.2020.06.033)

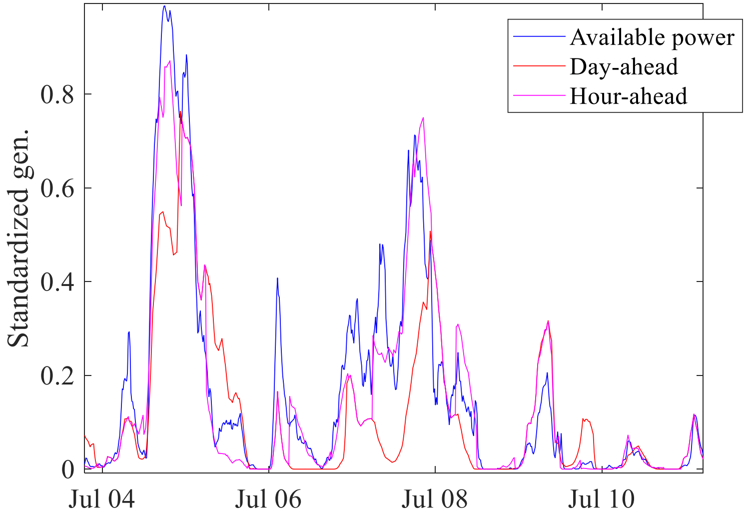
https://corres.windenergy.dtu.dk/

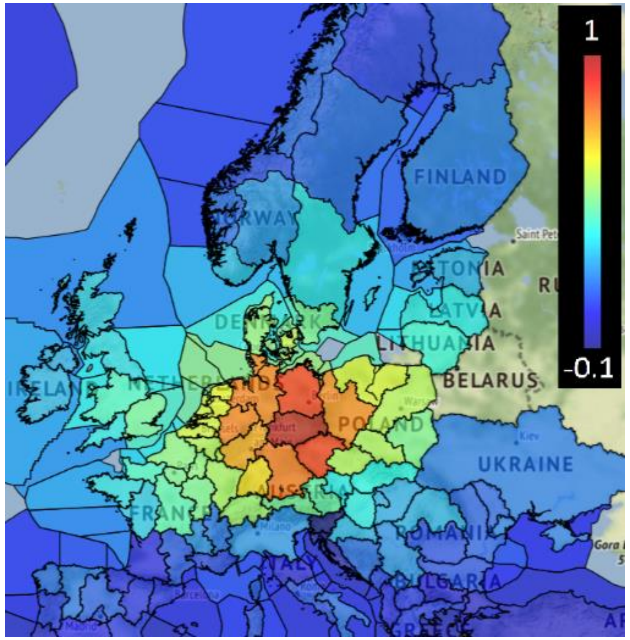
CorRES: Overview

- Correlations in renewable energy sources (CorRES)
  - **Tool to simulate wind and solar generation time series**
  - Developed at DTU Wind over many years

- **Used for power and energy system studies**
  - Large-scale runs (pan-European and beyond)
  - Can run 10000+ plants in one run
  - 35+ years on hourly (or higher) resolution

- **Used for plant-level analyses**
  - Detailed wake and storm shutdown modelling
  - Correlations between wind and solar generation and electricity price





Spatial correlations in wind generation looking from a German onshore region

CorRES: The two key parts of the model

Meteorological data

- ERA5
- ERA5-Land
- Global Wind Atlas (GWA)
- Also New European Wind Atlas (NEWA), and more

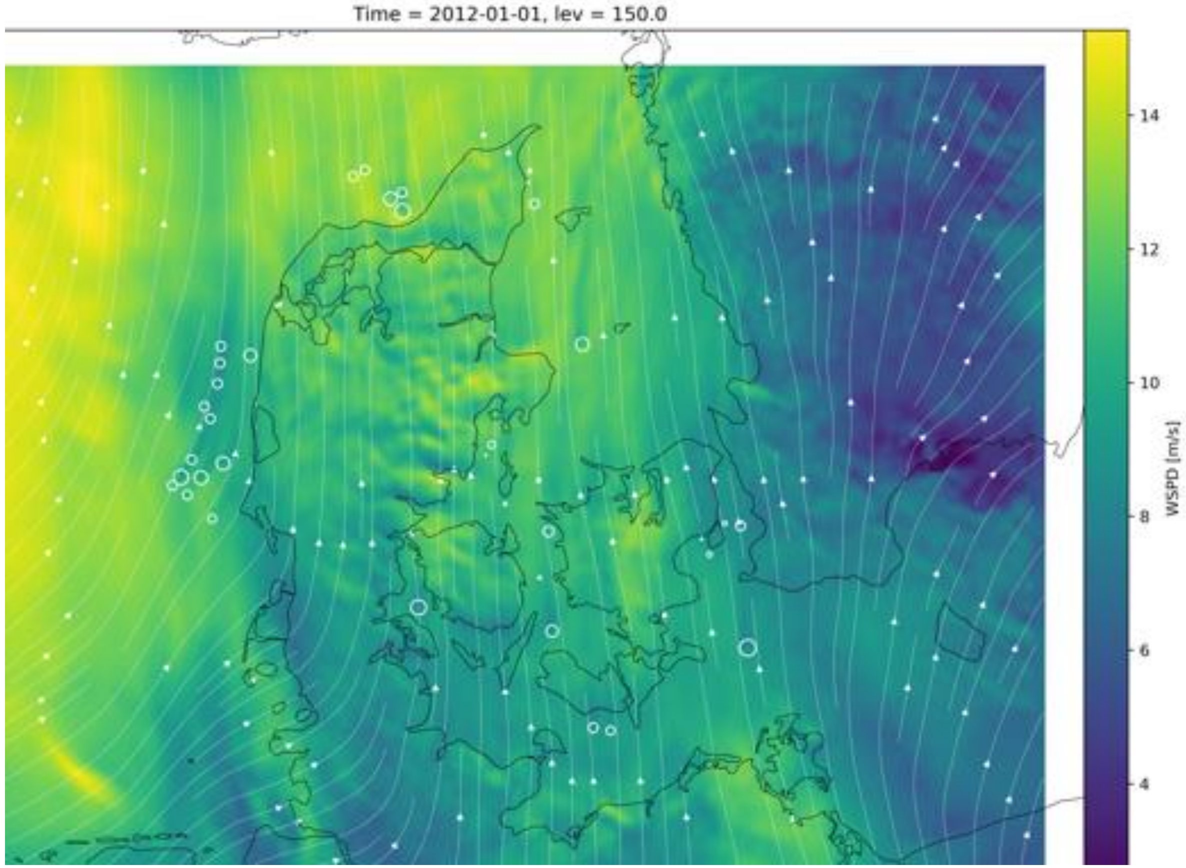
Conversion to power generation

- Wakes using PyWake
- Storm shutdown model
- PVLib for solar PV
- Turbine data
- Wind power plant (WPP) data

VRE time series

CorRES: Meteorological data

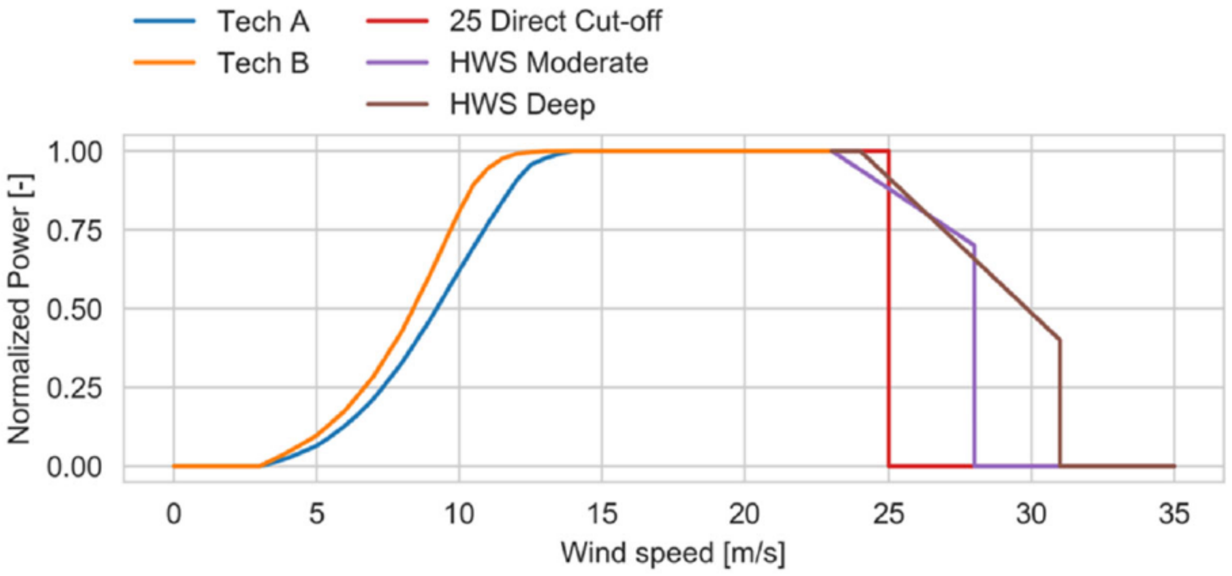
- **Weather reanalysis data**
  - ERA5: 1982-2021
  - Global
  - Also others, e.g., NEWA
- **Wind**
  - Linkage to GWA high resolution wind data
- **Solar**
  - ERA5-Land for higher resolution irradiance data
- Simultaneous running of 10000+ plants
  - Aggregated presentation of results



J. P. Murcia, et al., "Validation of European-scale simulated wind speed and wind generation time series", *Applied Energy*, 2022 (https://doi.org/10.1016/j.apenergy.2021.117794)

CorRES:
Wind conversion to power generation

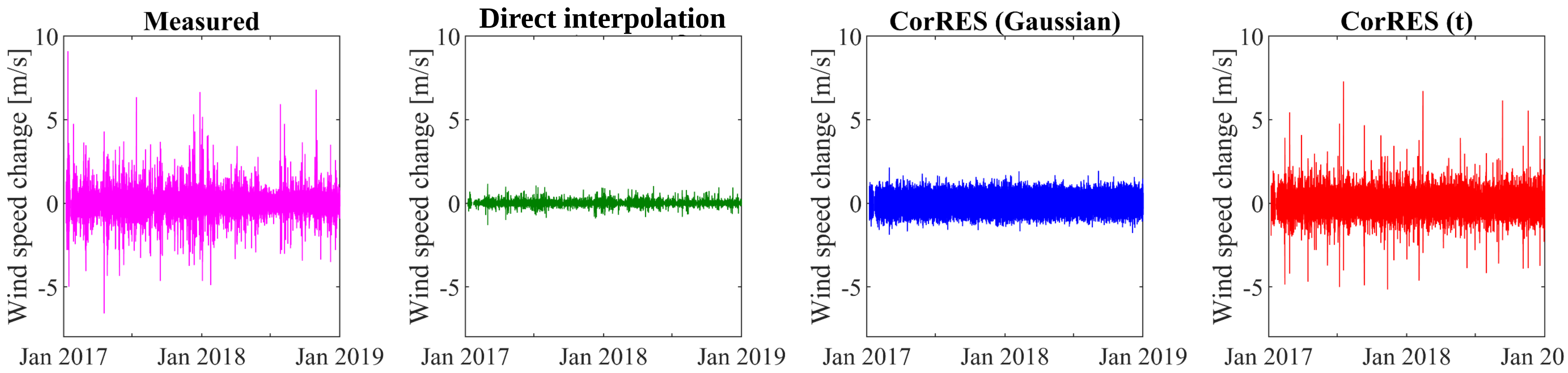
- **Wake losses**
  - Wake-impacted plant-level power curves using PyWake
  - Also farm-to-farm wakes
- **Different turbine types**
  - With unique power curves
  - **Including storm shutdown behaviour**
- Hub heights can also be changed



J. P. Murcia Leon et al., “Power Fluctuations In High Installation Density Offshore Wind Fleets”, *Wind Energy Science*, 2021 (https://doi.org/10.5194/wes-2020-95).

CorRES:
High temporal resolution via stochastic simulation

- **Up to 1-5 min resolution for wind**
  - Simultaneous running of a few hundred plants (usually applied for offshore plants)



10 min wind speed ramps in measured data (magenta) and in different stages of the CorRES simulation procedure: interpolated from hourly weather data (green) to the final result with stochastic simulation included (red)

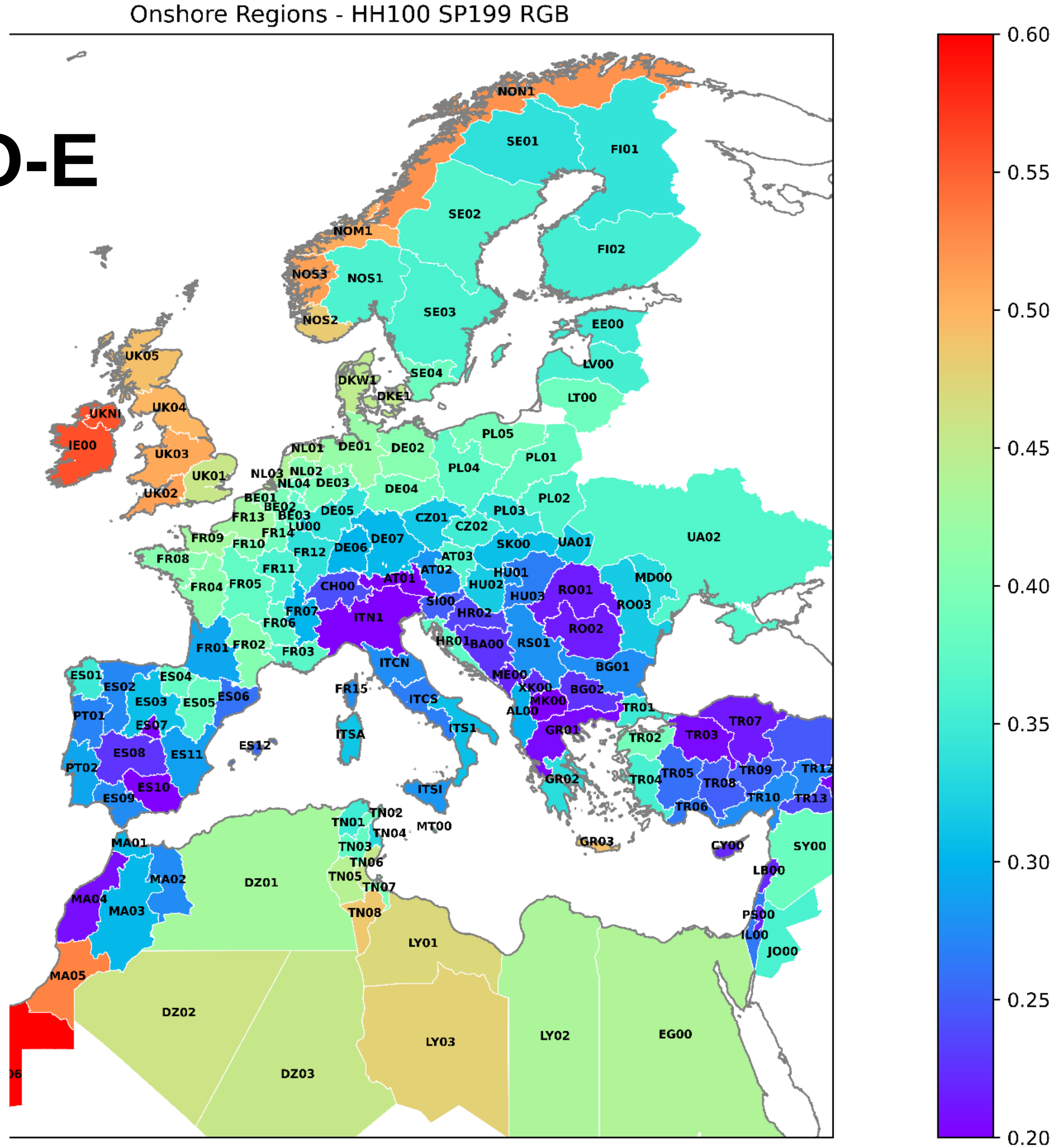
M. Koivisto et al., “Combination of meteorological reanalysis data and stochastic simulation for modelling wind generation variability”, *Renewable Energy*, 2020 (https://doi.org/10.1016/j.renene.2020.06.033).

J. P. Murcia Leon et al., “Power Fluctuations In High Installation Density Offshore Wind Fleets”, *Wind Energy Science*, 2021 (https://doi.org/10.5194/wes-2020-95).

CorRES use cases:
VRE simulations for ENTSO-E

- **Pan-European climate database (PECD):**
  - Database of weather driven time series
  - Wind & solar done with CorRES
  - Hourly resolution, 35+ years

- **Update of PECD data in Spring 2021**
  - Including large range of wind technologies for scenario building needs
  - **Available open access:** https://doi.org/10.11583/DTU.c.5939581



CorRES use cases:
Modelling offshore wind in North Sea energy hubs

- **Contracted research for the North Sea Wind Power Hub (NSWPH)**
  - NSWPH is a consortium of Energinet, Gasunie and TenneT
- DTU Wind Energy supported the study of offshore energy hubs and their energy system impacts in 2021
  - **Simulation of all VRE time series**

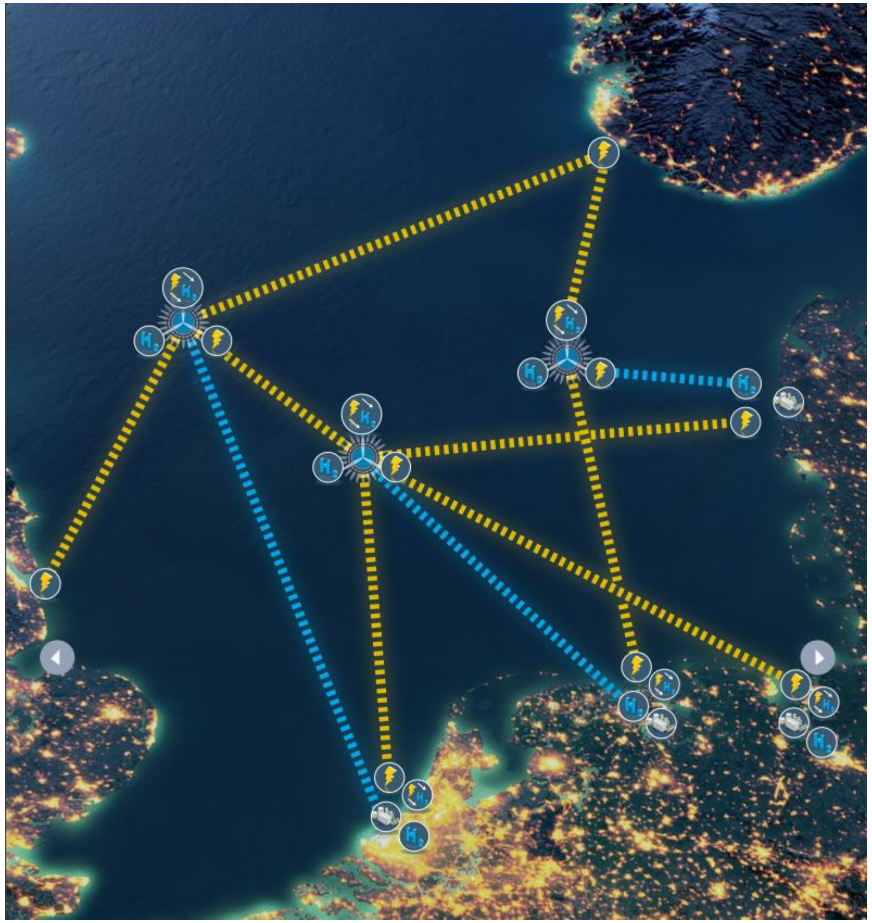
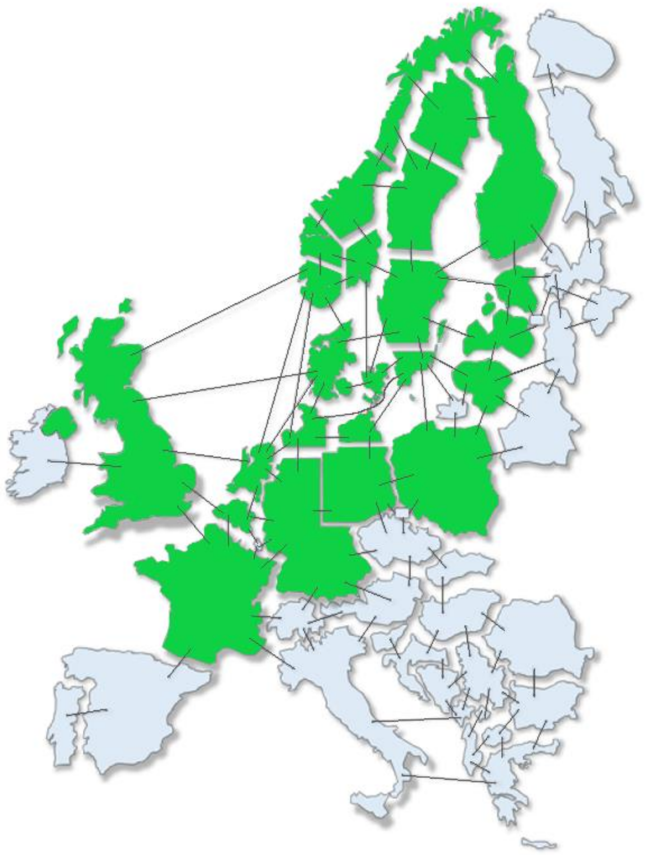


Figure from https://northseawindpowerhub.eu/

CorRES use cases:
In power and energy system analyses

CorRES → Balmorel → Scenarios



- For example for studying:
  - Offshore energy hubs & meshed grids
  - Impact of sector coupling
  - Impacts on future VRE plant revenues

J. Gea-Bermúdez et al., "Optimal generation and transmission development of the North Sea region: impact of grid architecture and planning horizon", *Energy*, 2020 (https://doi.org/10.1016/j.energy.2019.116512)

J. Gea-Bermúdez, et al., "The role of sector coupling in the green transition: A least-cost energy system development in Northern-central Europe towards 2050", *Applied Energy*, 2021 (https://doi.org/10.1016/j.apenergy.2021.116685)

Model assumptions

Model assumptions

- **Assumptions taken in the previous study are updated and were presented by Elia to stakeholders in Task Force of 01 April 2022**
  - Stakeholders were called to provide feedback before April 22, the latest
  - Inputs were received from turbine manufacturers, Belgian Offshore Platform and Public Services
  - Elia communicated the updated assumptions in its mail of 29/04/2022

- **At this point, the potential impact of gravel beds (excluding part of the zone for construction for ecologic reasons) is not included :**
  - There was no certainty on the exact surfaces to be excluded (and potential impact on the capacity installed and generation)
  - Impact on the system integration simulations (forecast errors, storms and ramps) is expected to be limited

Updates in the assumptions: Technology updates

- **Bigger turbines (17 and 20 MW)**
  - Larger rotors
  - Thus also higher hub heights

2022 update

Technology scenario (installations before 2030)	A	B
Rated power (MW)	17	17
Rotor diameter (m)	219	262
Hub height (m)	140	165
Specific power (W/m2)	450	316

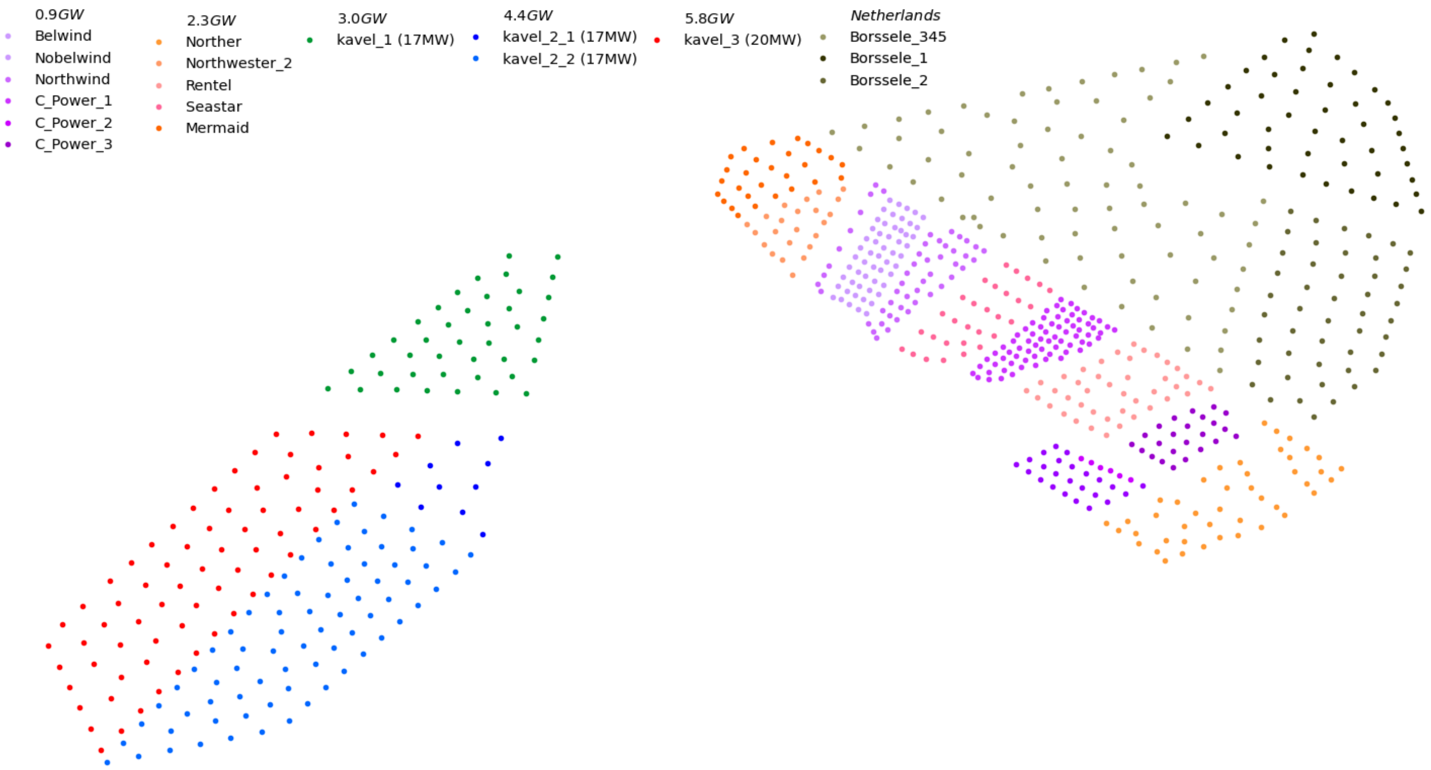
Technology scenario (installations in 2030)	A	B
Rated power (MW)	20	20
Rotor diameter (m)	238	284
Hub height (m)	150	175
Specific power (W/m2)	450	316

2020 report

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

Technology scenario	A	B
Rated power	12 MW	12 MW
Rotor diameter	184 m	220 m
Hub height	118 m	150 m
Specific power	450 W/m^2	316 W/m^2

Updates in the assumptions: Layout and installed GW



The map shows the full 5.8 GW scenario by 2030 (+ nearby Dutch plants):

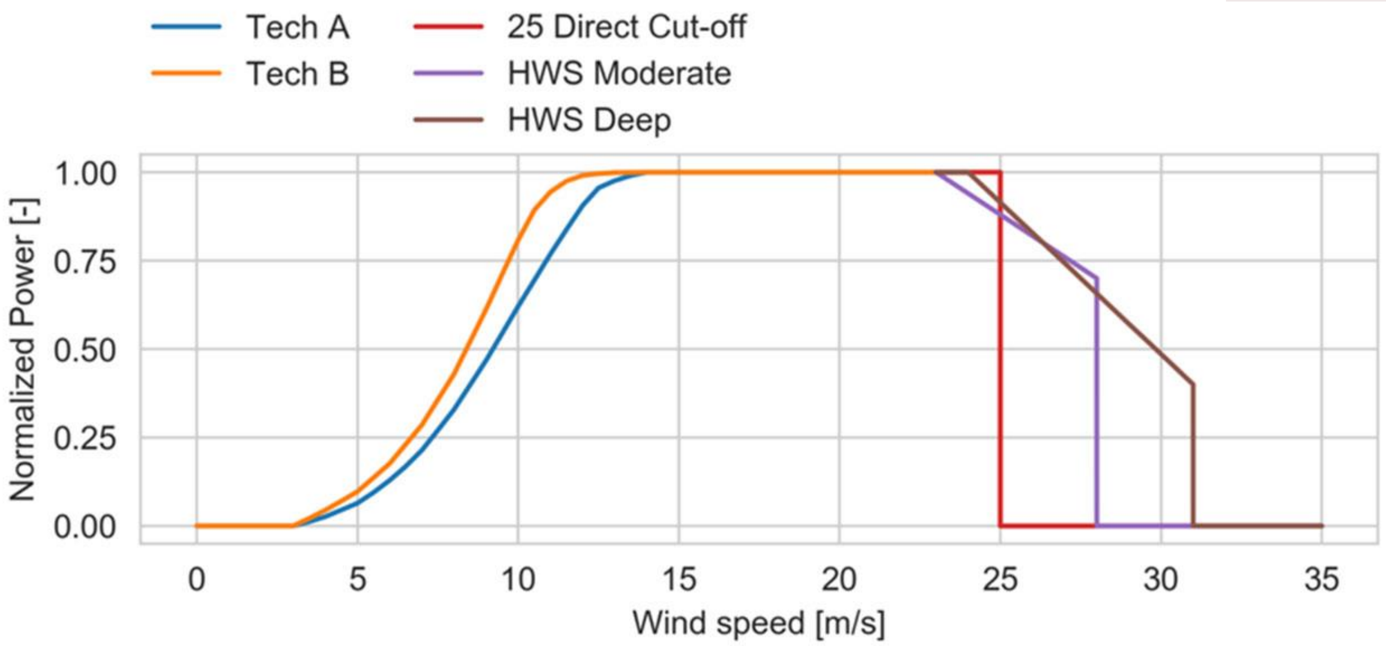
- 2.3 GW existing
- 3.5 GW new installations

Significantly higher than before

Area	Installed capacity (MW)	Turbine capacity (MW)	Area (km2)	MW/km2
Kavel 1 (-> 3.0 GW)	700	17	46	15.2
Kavel 2 (-> 4.4 GW)	1400	17	103	13.6
Kavel 3 (-> 5.8 GW)	1400	20	107	13.1

Turbine-level power curve shapes: Same as in the 2020 report

Technology scenario	A	B
Specific power (W/m2)	450	316



- Tech A and Tech B cover the range of specific powers expected towards 2030
- The “Deep” storm shutdown type aligns with the newest offshore wind power plants in Belgium

Updates in the modelling

- **Using newest meteorological reanalysis data**
  - Using ERA5 reanalysis data
  - Gives high correlation to measured data[1]
  - Used also in the 2021 PECD update for ENTSO-E
  - **Data available until the end of 2021**

- **Updated wake modelling**
  - Using newest models in the PyWake tool from DTU Wind Energy[2,3,4]
  - **Similar to the report “LCOE offshore wind in the Princess Elisabeth zone”, 3E, Sep 2021**
  - We consider also the Dutch offshore wind power plants’ impacts on the Belgian plants

[1] J. P. Murcia, et al., “Validation of European-scale simulated wind speed and wind generation time series”, *Applied Energy*, 2022 (https://doi.org/10.1016/j.apenergy.2021.117794)

[2] Haohua Zong and Fernando Porté-Agel, “A momentum-conserving wake superposition method for wind farm power prediction”, J. Fluid Mech. (2020), vol. 889, A8; doi:10.1017/jfm.2020.77

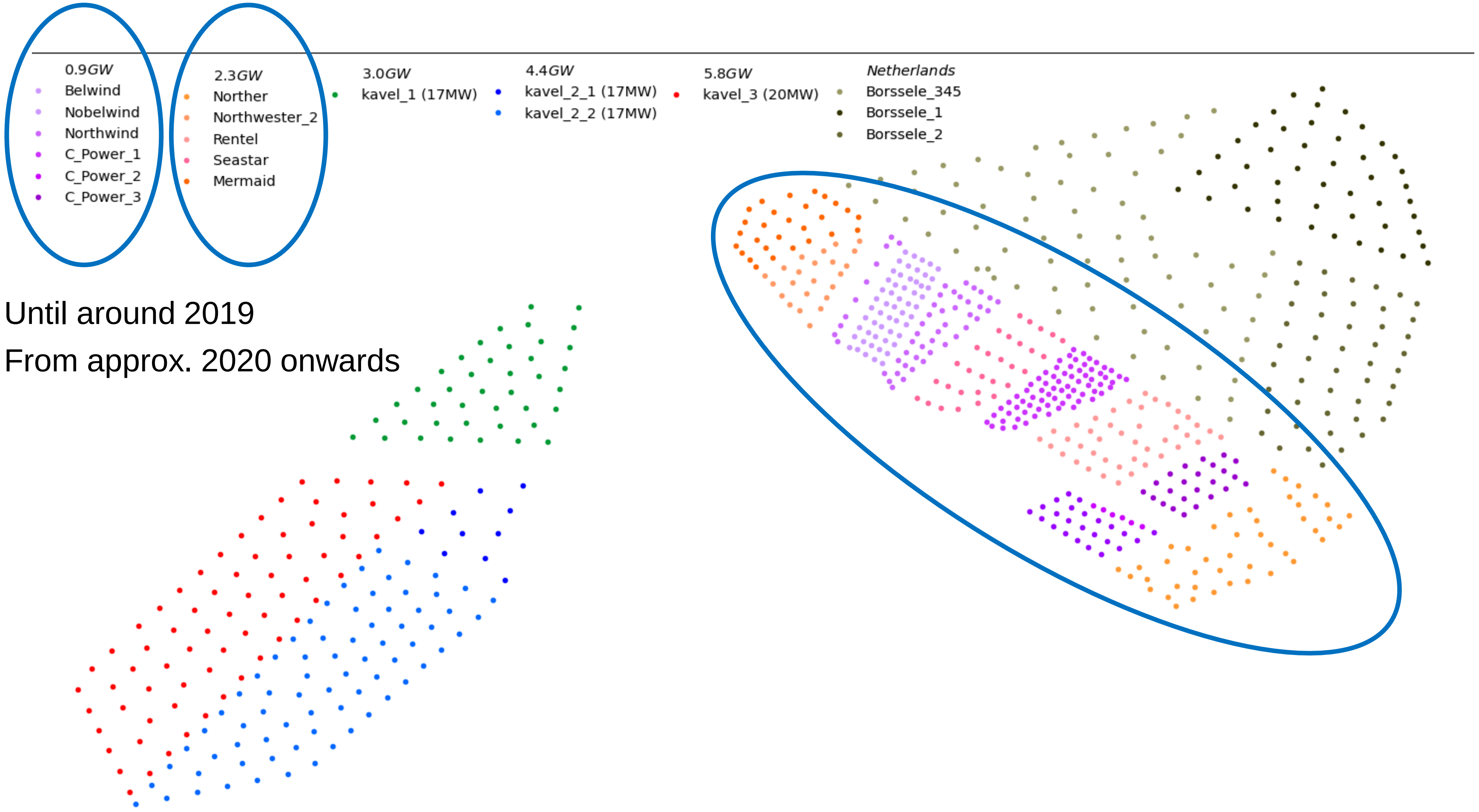
[3] N. Troldborg, A.R. Meyer Fortsing, “Assessing the blockage effect of wind turbines and wind farms using an analytical vortex model”, Wind Energy, 2016. https://doi.org/10.1002/we.2546

[4] Steen Frandsen's turbulence model implemented according to IEC61400-1, 2017

Model validation

- Validation is done using measured data of Belgian offshore wind power generation
    - And also measured wind speeds from the turbines
- **Validation is important to gain trust to the model**
    - It compares the simulated wind speed and generation time series to measurements
- **The same model is them applied to model scenarios of up to 5.8 GW of offshore wind in Belgium**

Update of model validation: Two cases studied



0.9 GW: Until around 2019

2.3 GW: From approx. 2020 onwards

Update of model validation: 0.9 GW case (877 MW)

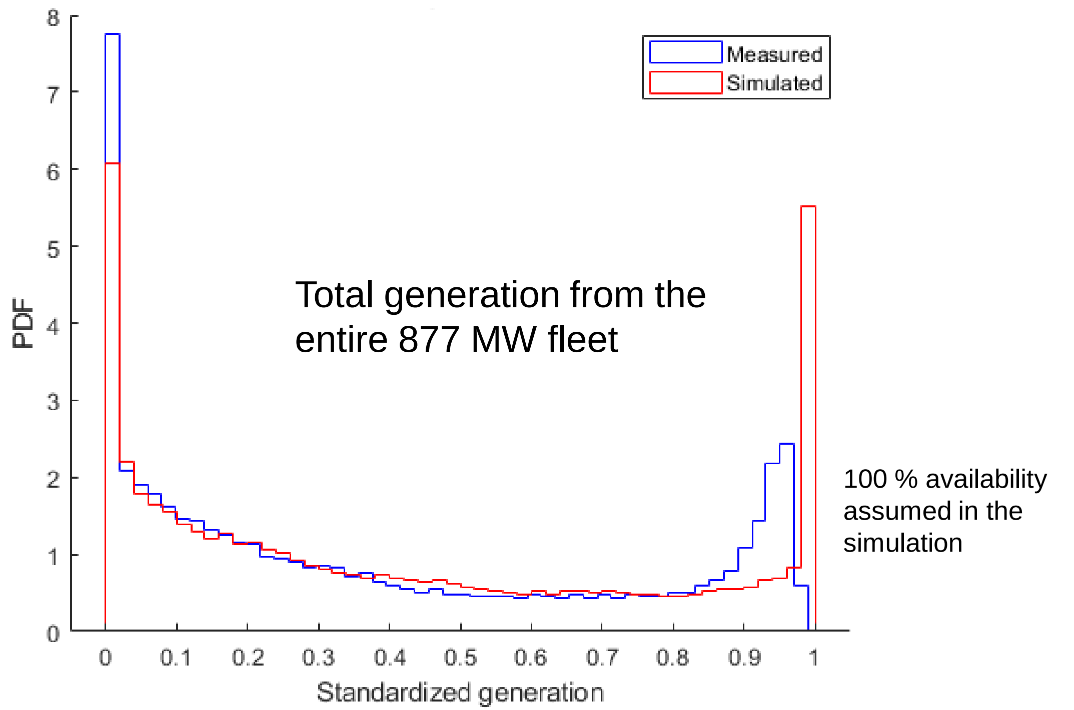
- Validation data from around mid-2017 until 2019

- **Capacity factors and generation distribution:**
  - **Good fit to measured data**
  - Note: the CorRES runs assume 100 % availability

- **Ramp distributions**
  - Fine fit to data
  - Similar to the 2020 report

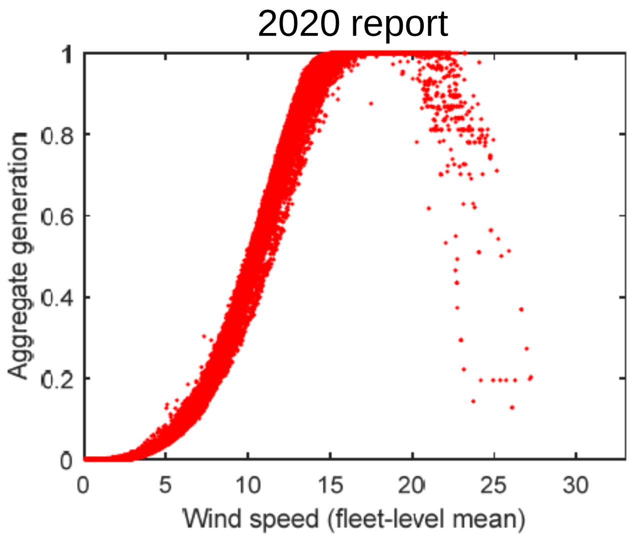
	Capacity factor	Standard deviation
Measured	0.382	0.343
Simulated	0.405	0.350
Simulated (5% unavailability)	0.385	
Simulated (2020 report)*	0.416	0.351

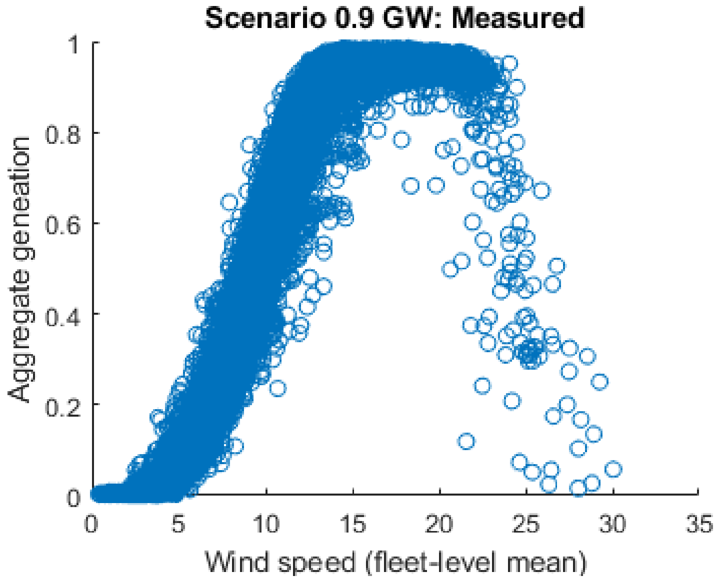
*Note that the simulated time period is not identical to the 2022 update

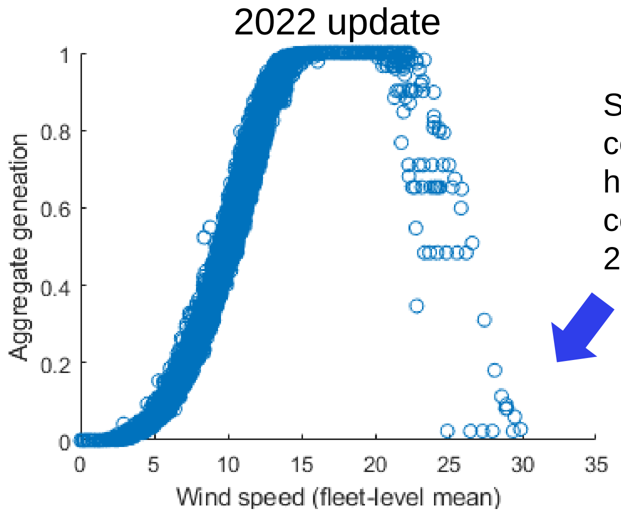


Update of model validation: 0.9 GW case (877 MW)

- Modelling of wind speed and generation
  - **Good fit to measured data**
  - **Including high wind events**



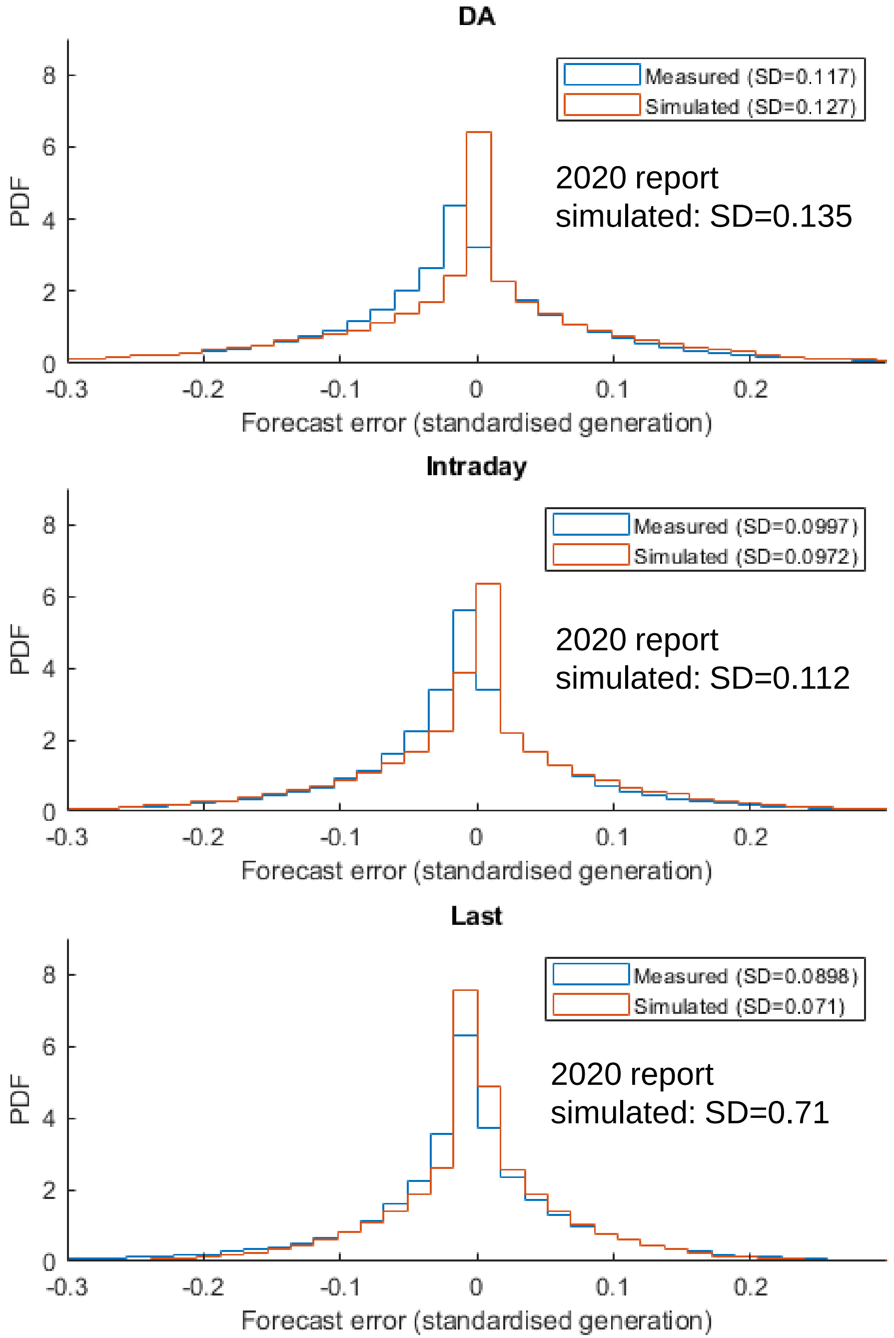




Slightly better coverage of very high wind speeds compared to the 2020 report

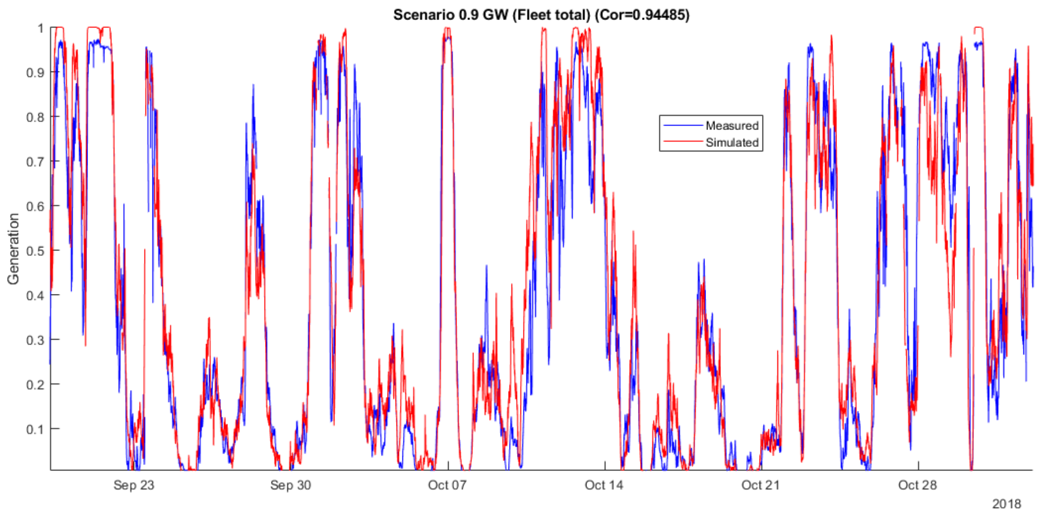
Update of model validation: 0.9 GW case (877 MW)

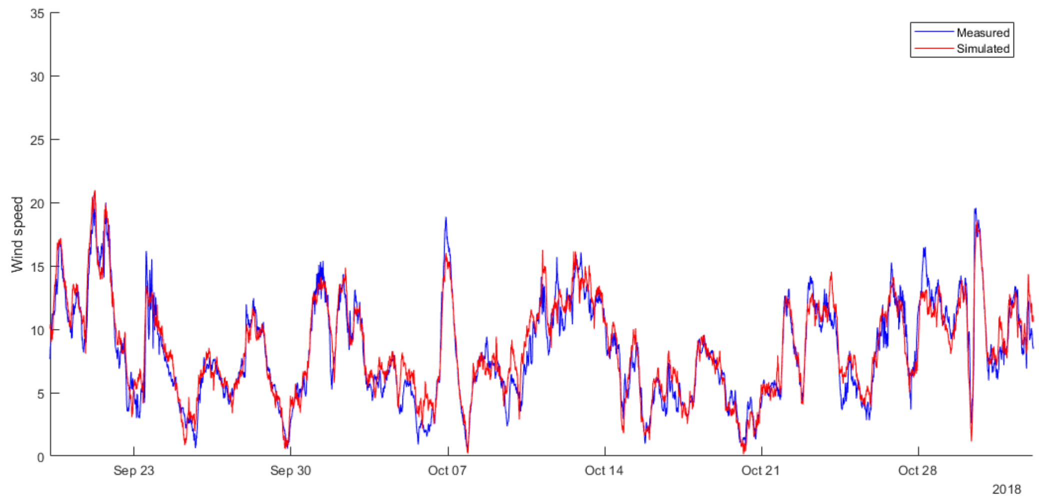
- Simulations in line with the measured forecast errors
- **Slightly better match to measurements compared to the 2020 report**



Update of model validation: 0.9 GW case (877 MW)

- **Correlation to measured data:**
  - Correlation between measured and simulated data: **0.94**
    - » Fleet-level time series
    - » 5 min resolution
  - **Higher than in the 2020 report (where it was < 0.9)**
    - » Due to the updated meteorological data

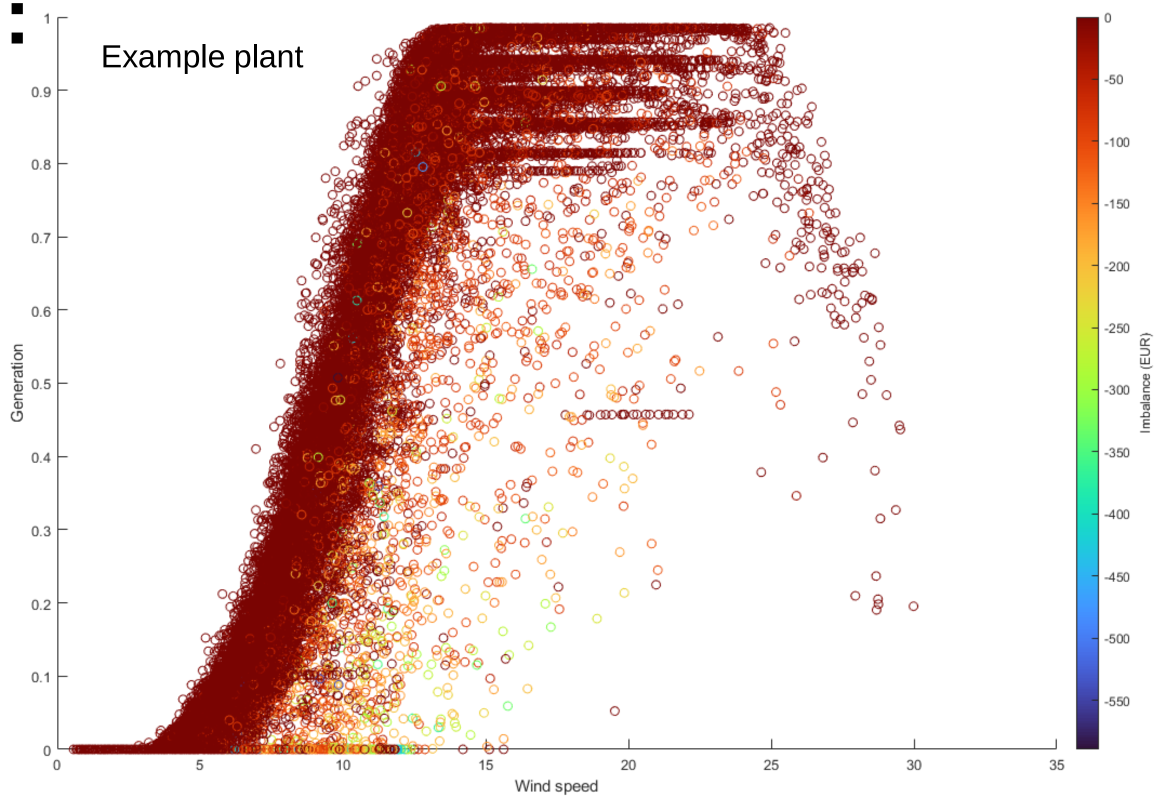


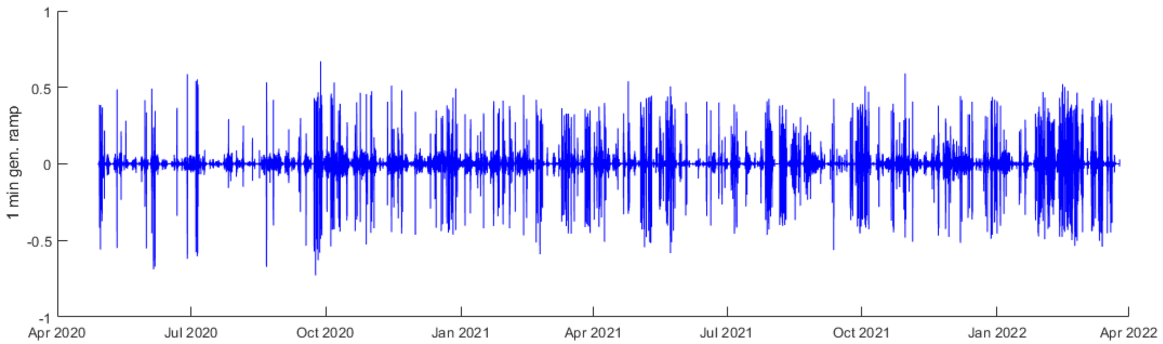


Update of model validation: 2.3 GW case

- **Data cleaning applied**
  - Lower generation following voluntary curtailment is filtered by removing periods where positive imbalance price is below -110 €/ MWh
  - Or if down regulation reported
  - Otherwise, same as in the 2020 report

- Without filtering, the 1 min ramps seem too high to be caused by weather-related events

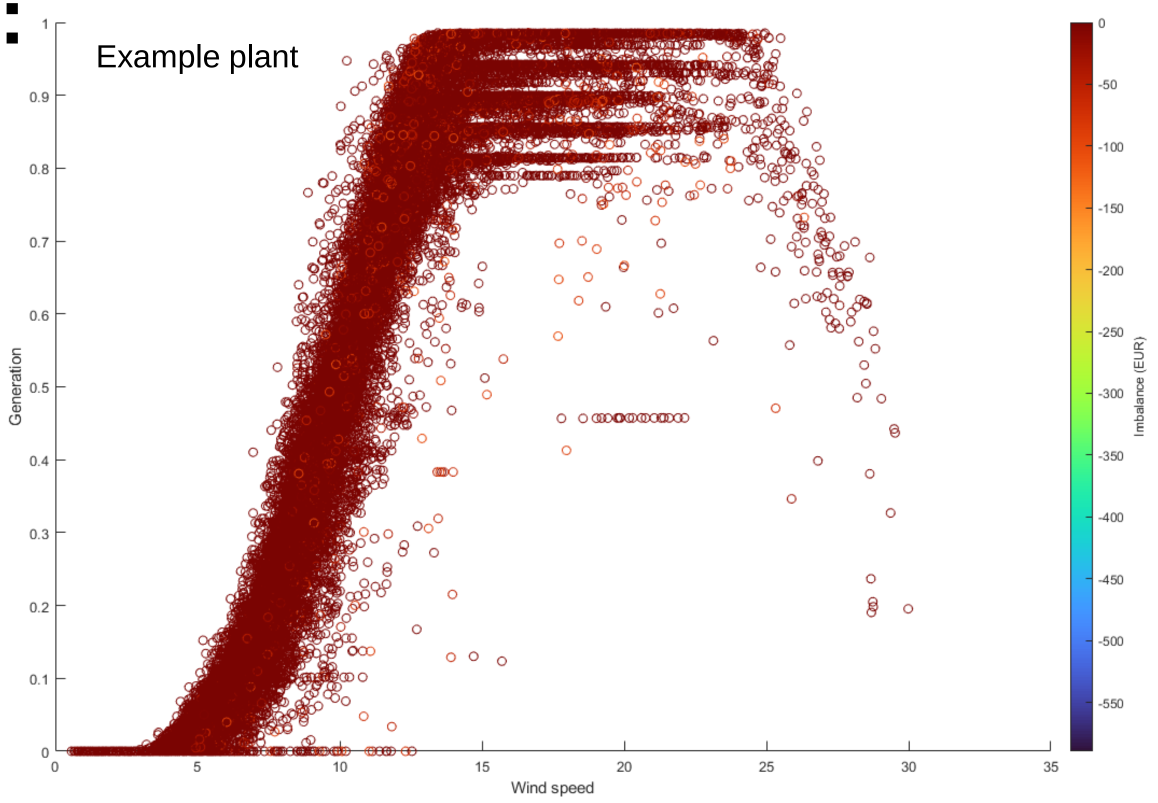


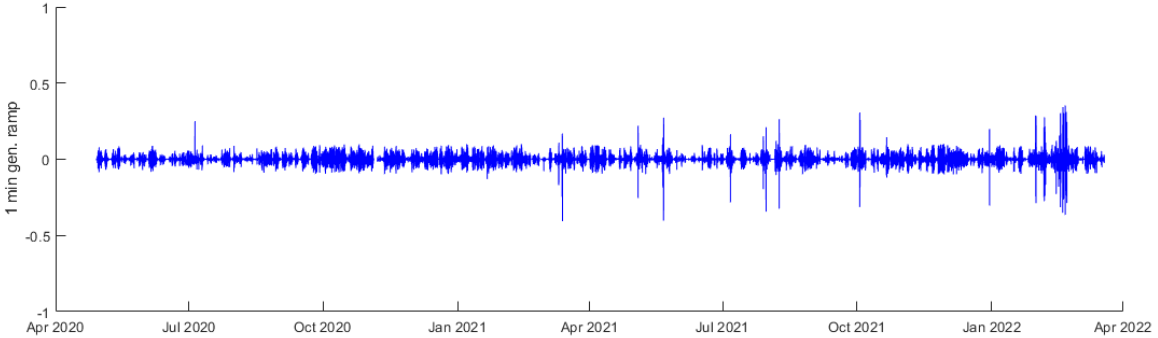


Update of model validation: 2.3 GW case

- **Data cleaning applied**
  - Lower generation following voluntary curtailment is filtered by removing periods where positive imbalance price is below -110 €/ MWh
  - Or if down regulation reported
  - Otherwise, same as in the 2020 report

- With filtering, the 1 min ramps represent weather related ramping



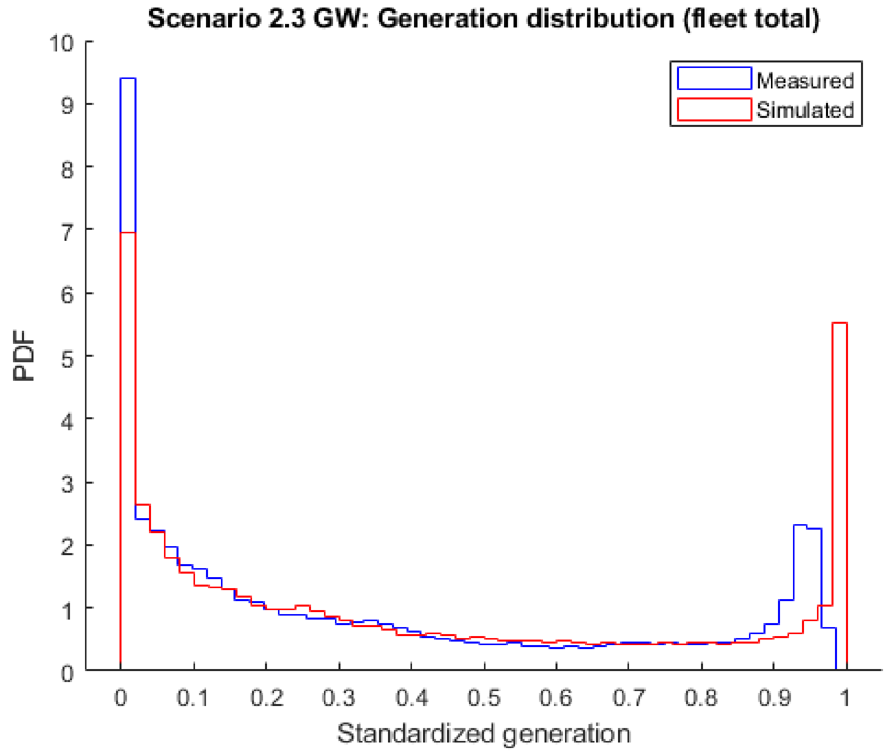


Update of model validation: 2.3 GW case

- Validation data from Dec 2020 until the end of 2021

- **Capacity factors and generation distribution:**
  - Simulated capacity factor (CF) somewhat higher than measured
  - The recently commissioned plants may not have generated at full capacity the whole time
    » Note: the CorRES runs assume 100 % availability

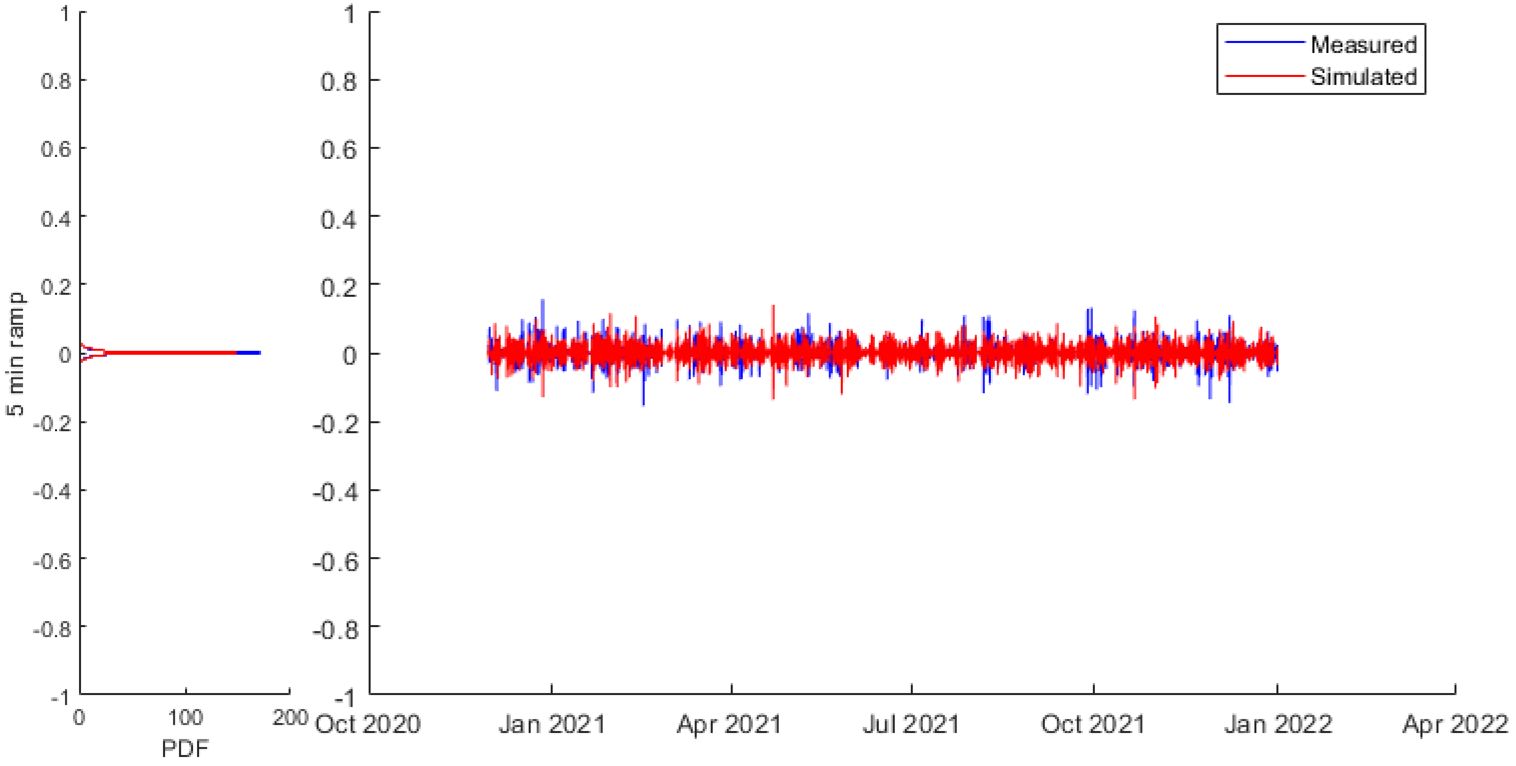
	Capacity factor	Standard deviation
Measured	0.348	0.339
Simulated	0.394	0.357
Simulated (5% unavailability)	0.375	



Update of model validation: 2.3 GW case

- **Ramp distributions**

- 5 min ramps well modelled

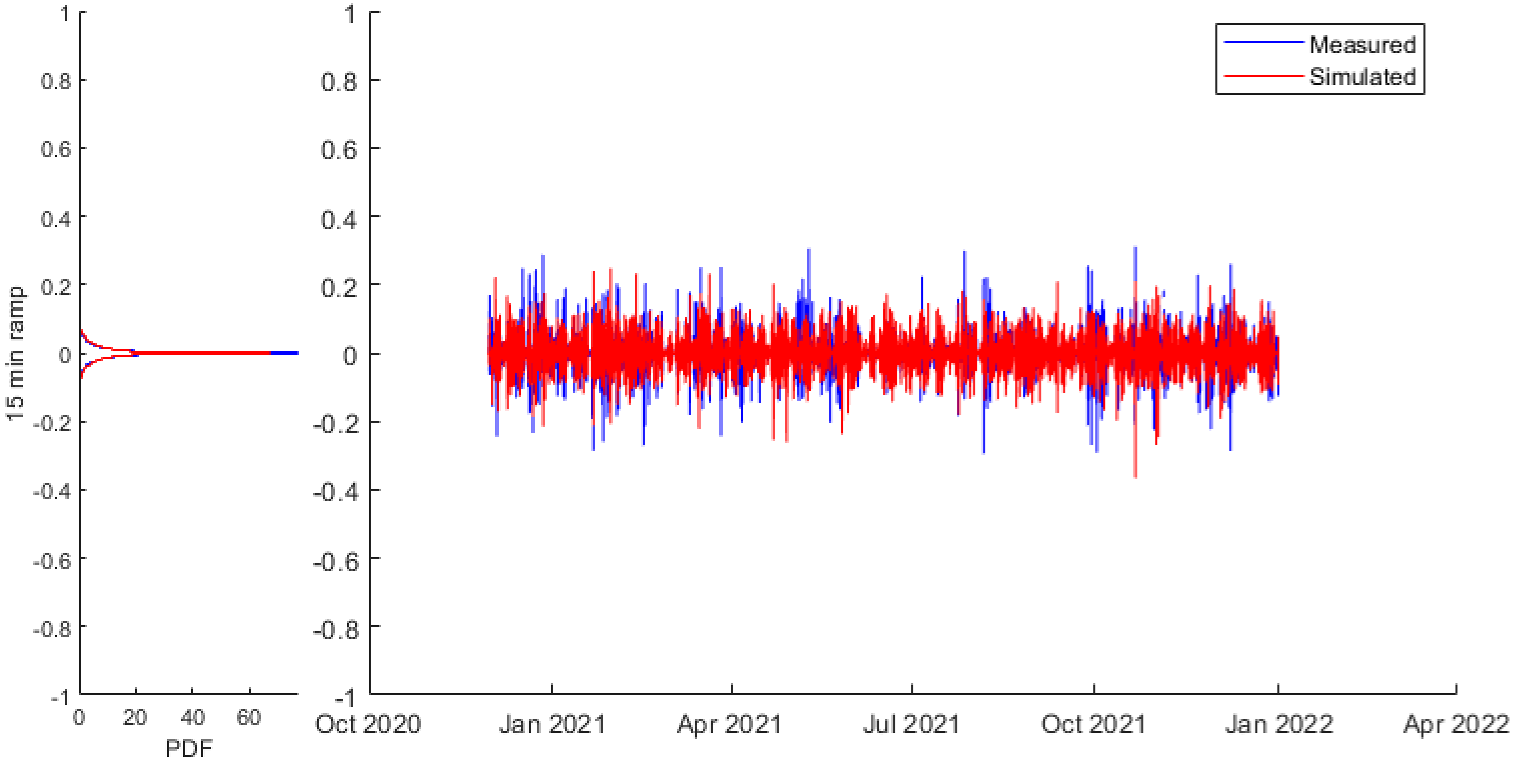


	mean	SD	min	Prct 0.1	Prct 1	Prct 5	Prct 95	Prct 99	Prct 99.9	max
Measured	0.000	0.011	-0.154	-0.062	-0.031	-0.016	0.016	0.032	0.064	0.156
Simulated	0.000	0.011	-0.136	-0.057	-0.032	-0.018	0.018	0.033	0.058	0.140

Update of model validation: 2.3 GW case

- **Ramp distributions**

- 15 min ramps well modelled
  - Based on 5 min resolution data

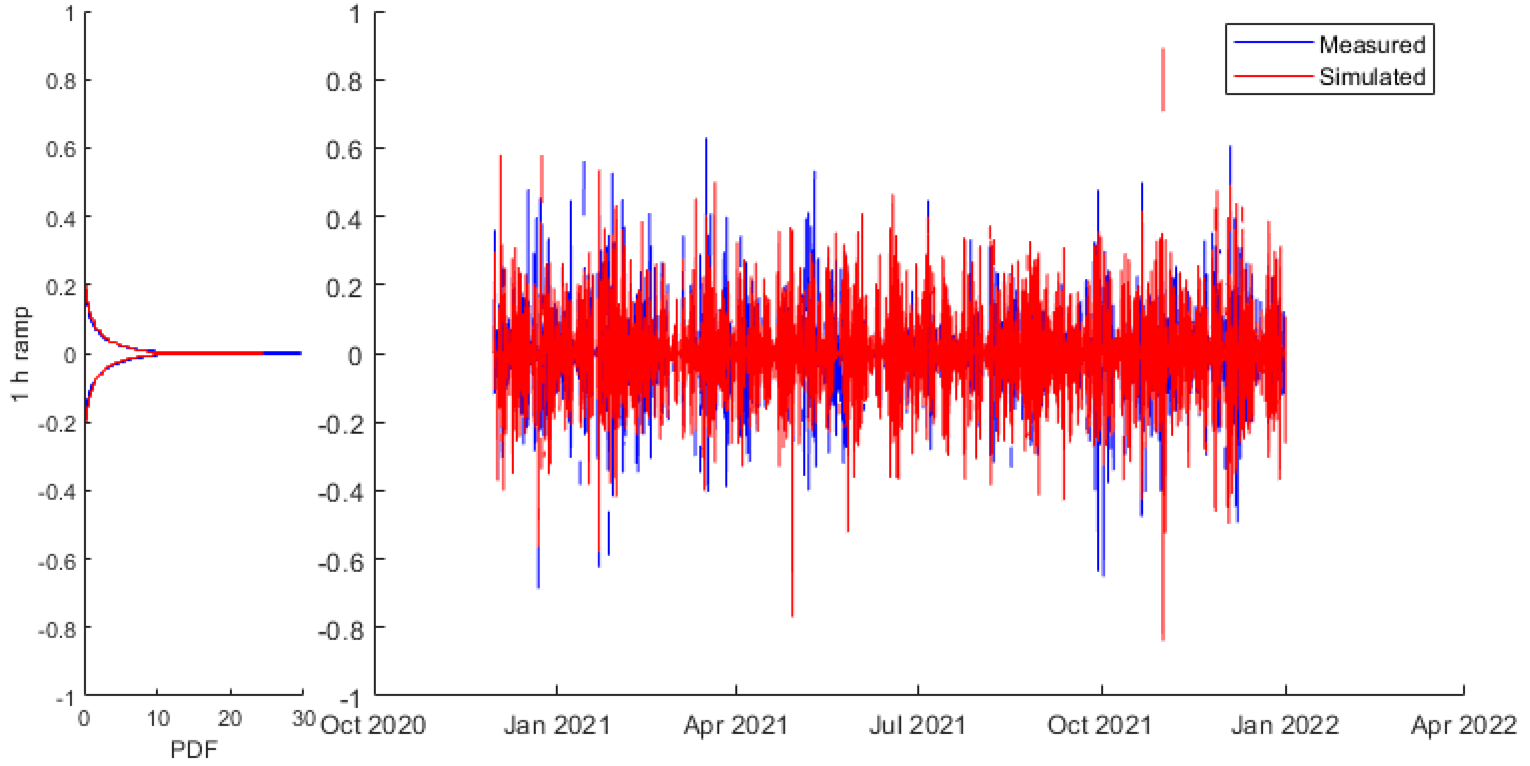


	mean	SD	min	Prct 0.1	Prct 1	Prct 5	Prct 95	Prct 99	Prct 99.9	max
Measured	0.000	0.027	-0.338	-0.153	-0.080	-0.040	0.042	0.083	0.162	0.311
Simulated	0.000	0.028	-0.365	-0.141	-0.079	-0.045	0.045	0.081	0.134	0.248

Update of model validation: 2.3 GW case

- **Ramp distributions**

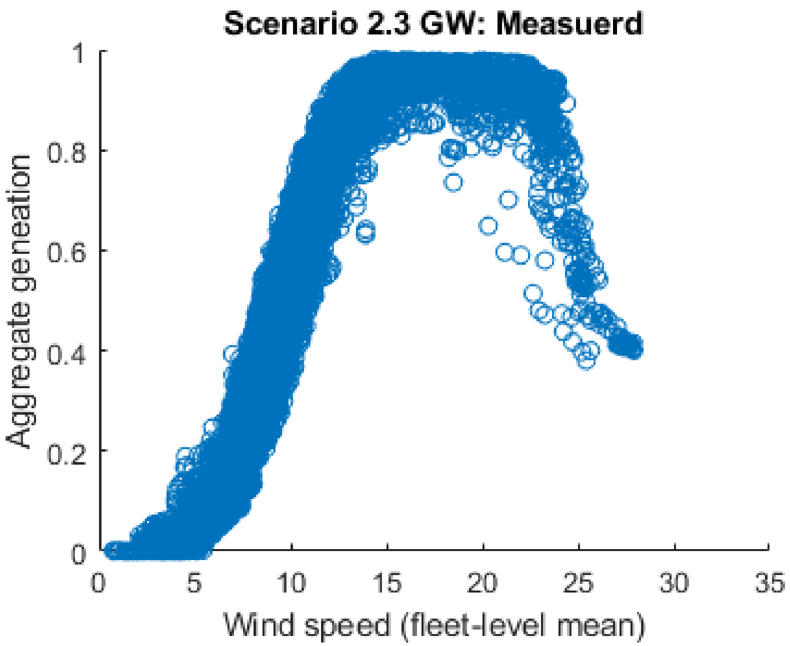
- 1 h ramps well modelled
  - Based on 5 min resolution data

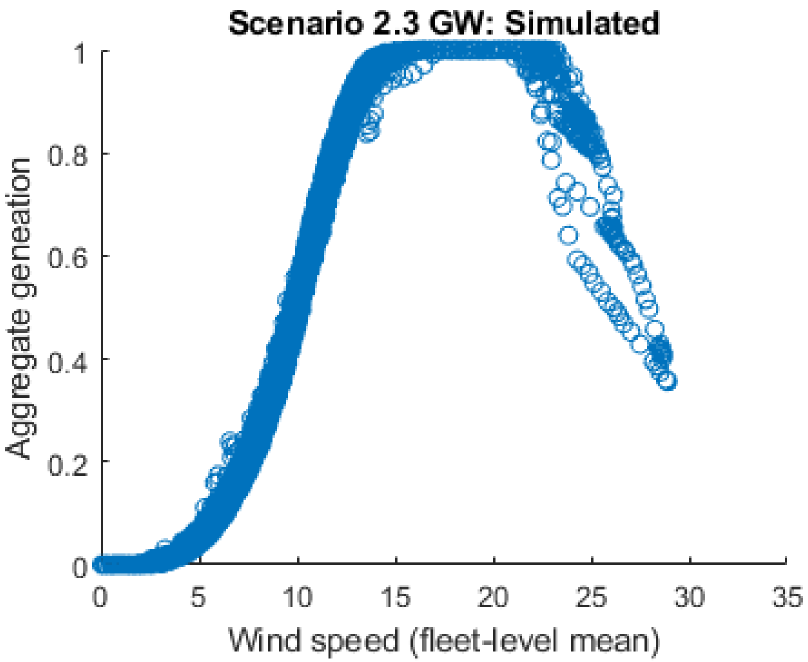


	mean	SD	min	Prct 0.1	Prct 1	Prct 5	Prct 95	Prct 99	Prct 99.9	max
Measured	-0.001	0.069	-0.686	-0.384	-0.205	-0.107	0.110	0.208	0.387	0.629
Simulated	0.000	0.077	-0.839	-0.405	-0.214	-0.124	0.124	0.231	0.380	0.892

Update of model validation: 2.3 GW case

- Modelling of wind speed and generation
  - **Good fit to measured data**
  - **Including high wind events**





Conclusion on model validation

- **The model is validated by means of a comparison of simulated generation and prediction profiles with observed generation and prediction profiles for the existing parks**
  - A filtering of negative price periods was implemented to better compare the simulated time series to the measurements
  - The observed results for the 2.3 GW case show higher unavailability than usual (5 %), increasing the deviation from the simulations (as the model does not consider unavailability)
  - Simulated forecasts are well in line with measurements

- **The model shows a similar / better accuracy compared to the previous study and is therefore suitable for the intended analyses**

Overview of the scenario results

1. Capacity factors and generation distributions
2. Extreme ramp events
3. Storm events and related ramps
4. Forecast errors

- **Results are statistics over the whole 40-year simulation period**
  - **From1982 to 2021, on 5 min resolution**

Results:
Capacity factor (CF) and standard deviation (SD)

2022 update

			CF	SD
5.8 GW	Tech A	25 m/s	0.436	0.362
		Moderate	0.437	0.363
		Deep	0.438	0.363
	Tech B	25 m/s	0.472	0.369
		Moderate	0.474	0.370
		Deep	0.475	0.370

2020 report

			CF	SD
4.4 GW	Tech A	25 m/s	0.449	0.354
		Moderate	0.450	0.354
		Deep	0.450	0.355
	Tech B	25 m/s	0.485	0.357
		Moderate	0.487	0.358
		Deep	0.488	0.358

Overall, similar results compared to the 4.4 GW scenarios in the 2020 report

- **CFs slightly lower**
  - CFs pushed up due to higher hub heights and larger turbines, and down due to increased density (and therefore increased wake losses)
- SDs slightly higher
  - Impacted by higher hub heights
  - **Model and weather data updates also has an impact**

Results:
5 min ramps (#days per year, wind speed < 20 m/s)

2022 update: 4.4 GW scenario

			Negative ramp (GW)									Positive ramp (GW)								
			5.0	4.0	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	4.0	5.0
4.4 GW	Tech A	25 m/s							0.1	0.8	7.9	8.9	0.9	0.1						
		Moderate								0.6	7.7	8.7	0.8							
		Deep								0.6	7.7	8.6	0.7							
	Tech B	25 m/s							0.1	1.1	10	10	1.1	0.1						
		Moderate								0.9	9.9	9.8	1.0							
		Deep								0.9	9.9	9.8	1.0							

2022 update: 5.8 GW scenario

			Negative ramp (GW)									Positive ramp (GW)								
			5.0	4.0	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	4.0	5.0
5.8 GW	Tech A	25 m/s							0.1	2.5	22	24	2.0	0.1						
		Moderate								2.4	22	24	1.9							
		Deep								2.4	22	24	1.9							
	Tech B	25 m/s							0.1	3.0	29	31	2.8	0.1						
		Moderate							0.1	2.9	29	31	2.7							
		Deep							0.1	2.9	29	31	2.7							

2020 report

			Negative ramp (GW)									Positive ramp (GW)								
			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
4.4 GW	Tech A	25 m/s							0.0	0.9	9.9	10.1	1.1							
		Moderate								0.3	9.1	9.4	0.4							
		Deep								0.2	9.0	9.4	0.4							
	Tech B	25 m/s							0.0	1.3	12.6	12.4	1.2							
		Moderate								0.5	11.7	11.5	0.5							
		Deep								0.5	11.6	11.5	0.5							

- **The 4.4 GW scenarios are similar for the 2022 update and 2020 report**
  - Note that the 2022 run 4.4 GW scenario is different from the 2020 report 4.4 GW scenario in terms of plant layouts and technology assumptions
- **The 5.8 GW scenario increases the likelihood of a high ramp compared to the 4.4 GW scenario**

Results:
1 h ramps (#days per year, wind speed < 20 m/s)

2022 update: 4.4 GW scenario

			Negative ramp (GW)									Positive ramp (GW)								
			5.0	4.0	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	4.0	5.0
4.4 GW	Tech A	25 m/s			0.0	0.1	1.4	11	75	243	296	294	241	81	15	2.8	0.7	0.1		
		Moderate			0.0	0.1	1.4	11	75	243	296	294	241	81	15	2.8	0.7	0.1		
		Deep			0.0	0.1	1.4	11	75	243	296	294	241	81	15	2.8	0.7	0.1		
	Tech B	25 m/s			0.0	0.2	2.1	14	85	246	297	294	244	87	16	2.6	0.6	0.1		
		Moderate			0.0	0.2	2.1	14	85	246	297	294	244	87	16	2.6	0.6	0.1		
		Deep			0.0	0.2	2.1	14	85	245	297	294	244	87	16	2.6	0.6	0.1		

2022 update: 5.8 GW scenario

			Negative ramp (GW)									Positive ramp (GW)								
			5.0	4.0	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	4.0	5.0
5.8 GW	Tech A	25 m/s		0.1	0.3	2.3	9.6	43	148	274	309	308	273	151	49	13	3.9	1.2	0.1	
		Moderate		0.1	0.3	2.3	9.6	43	148	274	309	308	273	151	49	13	3.9	1.2	0.1	
		Deep		0.1	0.3	2.3	9.6	43	148	274	309	308	273	151	49	13	3.9	1.2	0.1	
	Tech B	25 m/s		0.1	0.6	3.4	13	53	161	275	308	307	274	163	57	17	4.1	1.1	0.1	
		Moderate		0.1	0.6	3.4	13	53	161	275	308	307	274	163	57	16	4.1	1.1	0.1	
		Deep		0.1	0.6	3.4	13	53	161	275	308	307	274	163	57	16	4.1	1.1	0.1	

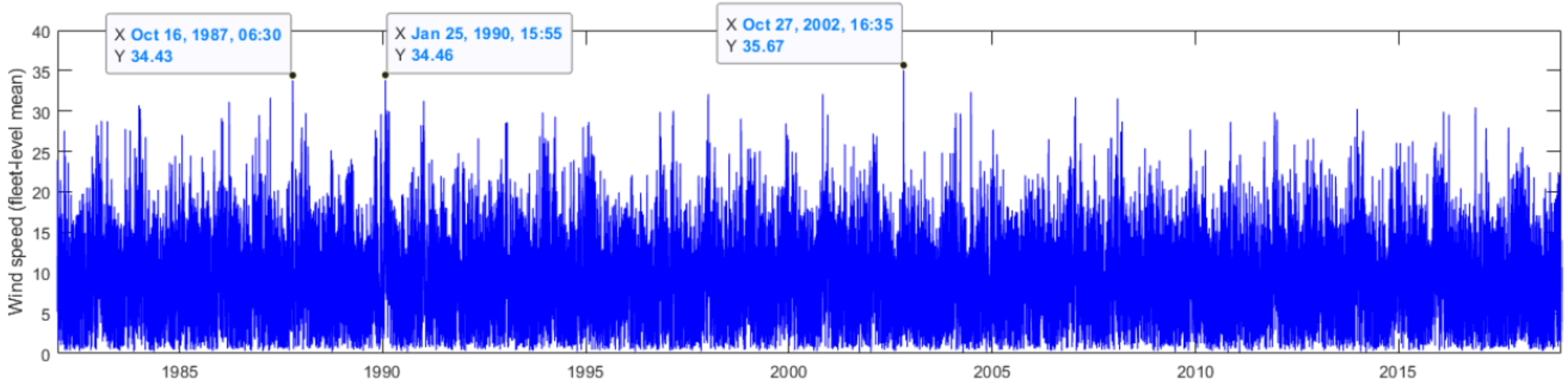
2020 report

			Negative ramp (GW)									Positive ramp (GW)								
			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
4.4 GW	Tech A	25 m/s			0.1	0.6	2.9	15.8	93.3	262.2	304.1	301.5	261.1	104.1	22.6	4.6	1.1	0.1	0.0	0.0
		Moderate			0.1	0.6	2.9	15.8	93.2	262.2	304.1	301.5	261.1	104.1	22.5	4.6	1.1	0.1	0.0	0.0
		Deep			0.1	0.6	2.9	15.8	93.2	262.2	304.1	301.5	261.1	104.1	22.5	4.6	1.1	0.1	0.0	0.0
	Tech B	25 m/s			0.1	0.7	3.4	19.1	100.2	264.4	304.5	303.1	265.2	106.3	23.4	4.2	0.8	0.2	0.0	0.0
		Moderate			0.1	0.7	3.4	19.1	100.1	264.3	304.5	303.0	265.1	106.2	23.2	4.2	0.8	0.2	0.0	0.0
		Deep			0.1	0.7	3.4	19.1	100.1	264.3	304.5	303.0	265.1	106.2	23.2	4.2	0.8	0.2	0.0	0.0

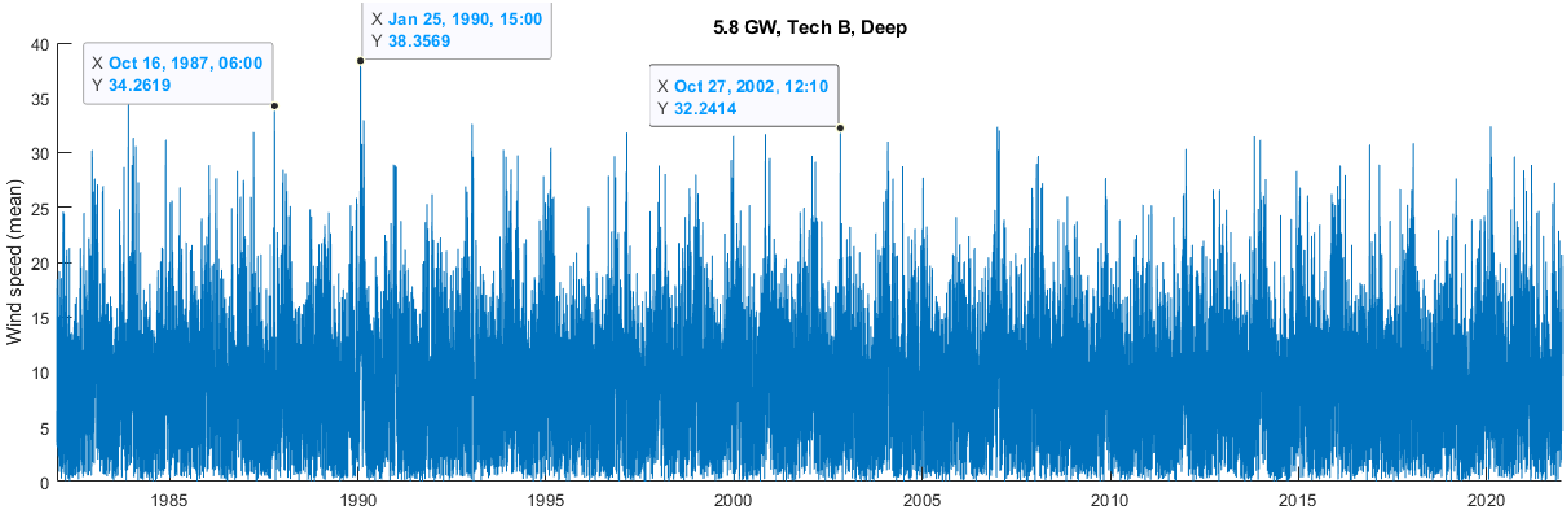
- **The 4.4 GW scenarios are similar for the 2022 update and 2020 report**
  - However, the likelihoods of high ramp events are estimated somewhat lower in the 2022 update
    - Mainly due to the updated weather data
    - As validation with the new model is good/better than with the old model, the results are considered valid
  - The single event causing the > 4.0 GW ramp in the 2020 report was not evident in the 2022 update
- **The 5.8 GW scenario increases the high ramp likelihoods compared to the 4.4 GW scenario significantly**

Results: Extreme storm events

2020 report



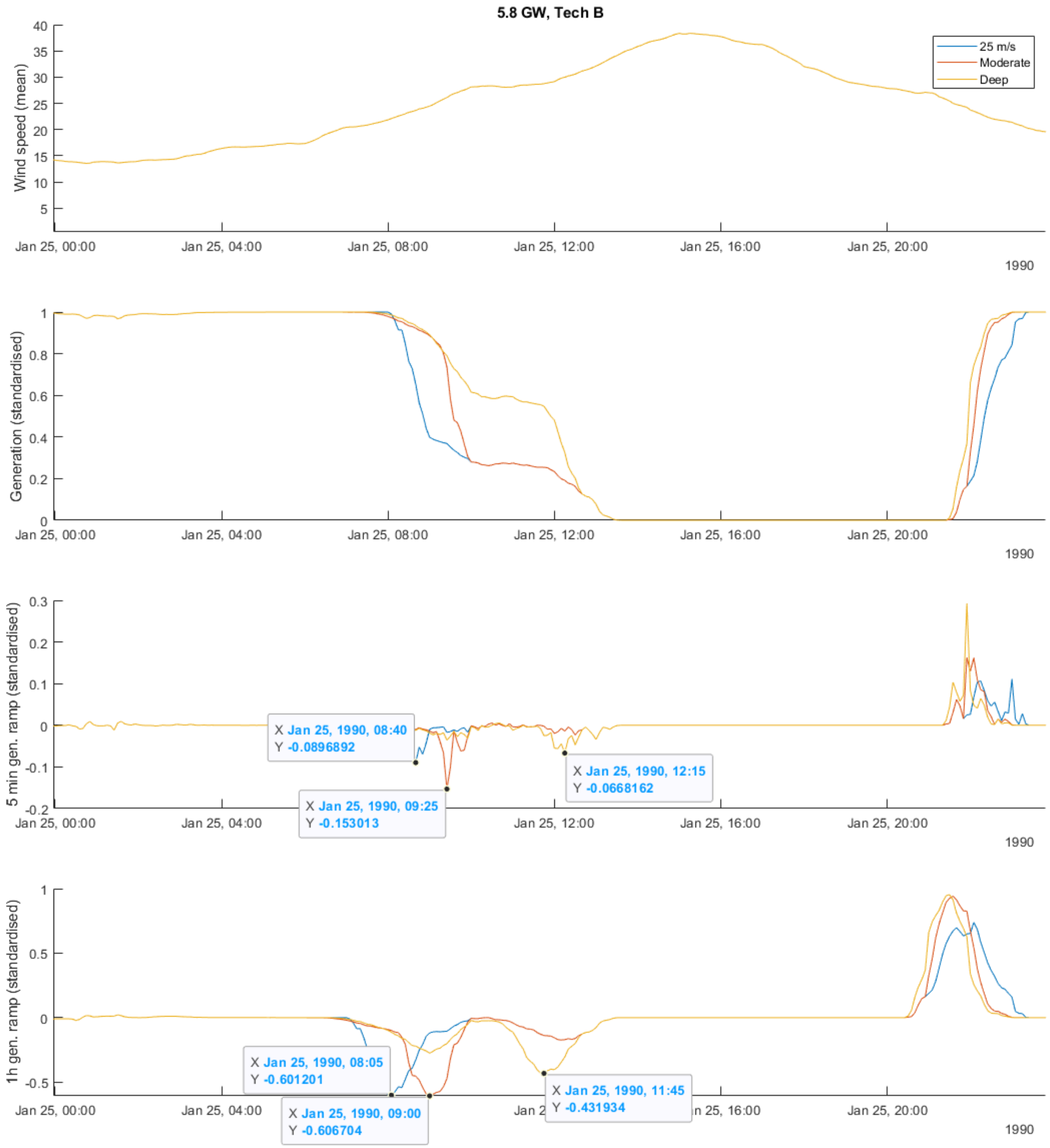
2022 update



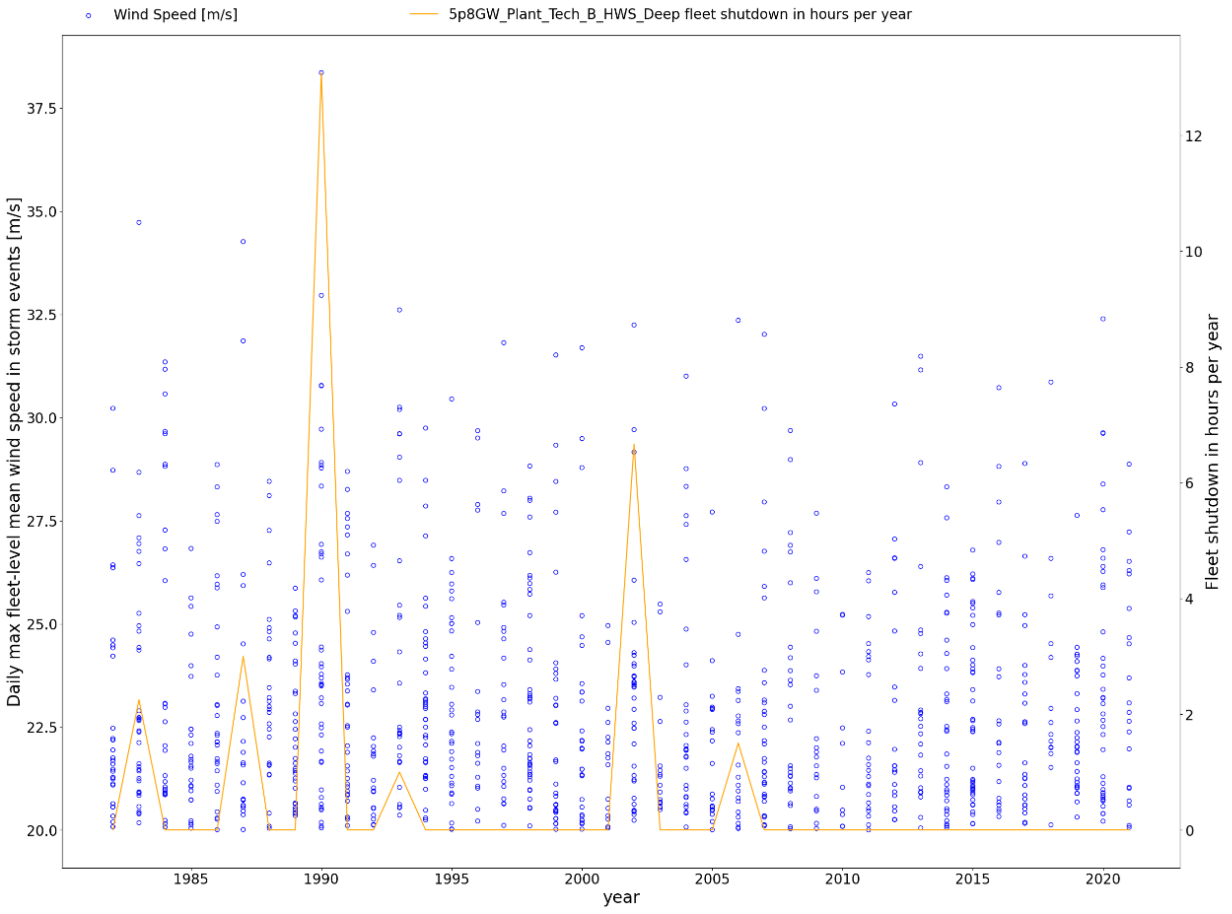
- **The Jan 25 1990 peak wind speed is estimated higher in the 2022 update**
    - Generally, peak wind speeds are similar than in the 2020 report

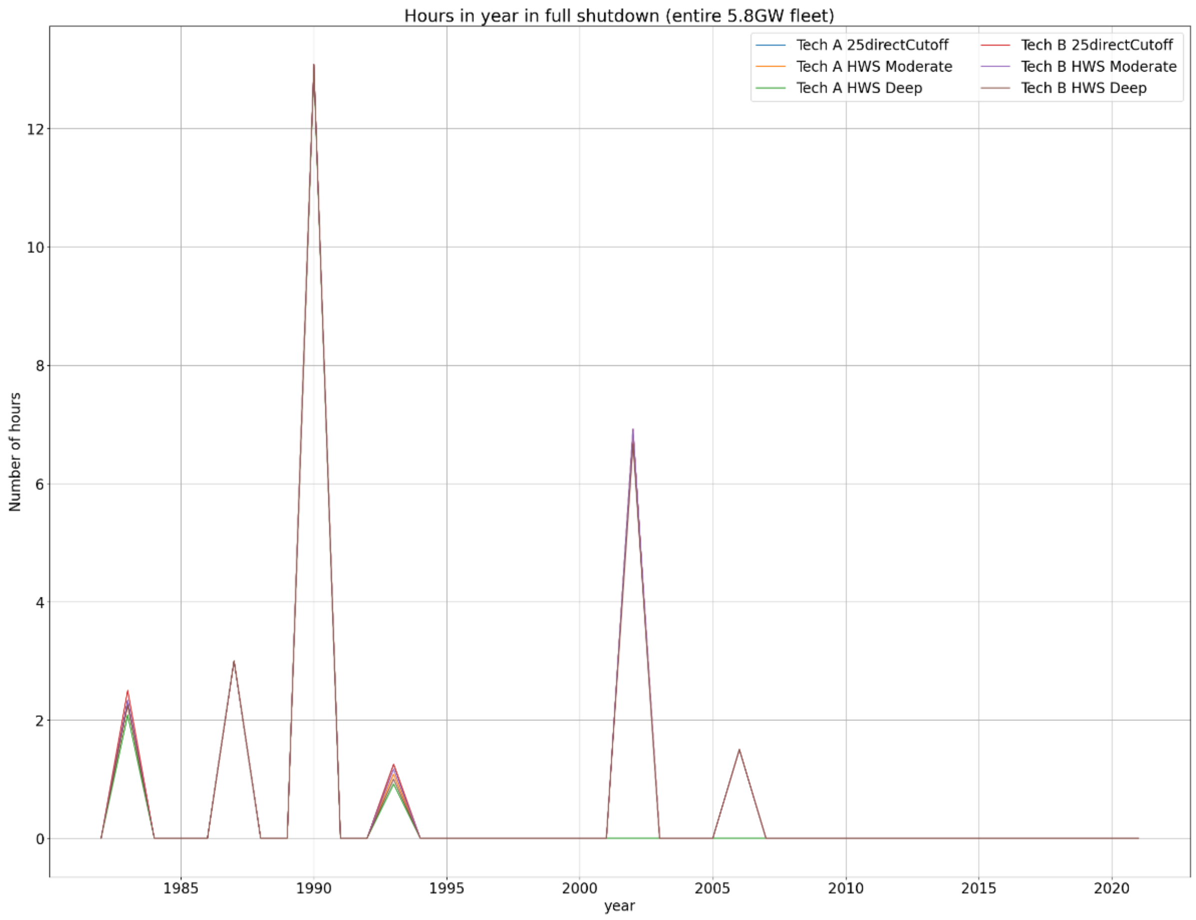
Results:
The whole fleet can be in storm shutdown

- **Similar result as in the 2020 report**
- In most cases, the “Deep” shutdown technology shows the lowest negative ramps
- **Note about the up ramps after storm:**
  - Assumed similar for all shutdown technologies
  - But can be controlled to be lower



Results:
The whole fleet can be in storm shutdown





- **The likelihoods of the whole fleet being in complete storm shutdown are similar for the 5.8 GW scenario (shown above) compared to the 4.4 GW scenario in the 2020 report**

Results:
5 min ramps (#days per year, wind speed > 20 m/s)

2022 update: 4.4 GW scenario

			Negative ramp (GW)									Positive ramp (GW)							
			5.0	4.0	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	4.0	5.0
4.4 GW	Tech A	25 m/s							0.2	2.2	5.4	5.1	2.0	0.4	0.0					
		Moderate							0.1	1.1	2.9	3.1	1.3	0.2	0.0					
		Deep								0.1	0.8	1.6	0.5	0.1	0.0					
	Tech B	25 m/s							0.3	2.4	6.4	6.2	2.0	0.3	0.0					
		Moderate							0.1	1.6	3.4	3.5	1.7	0.3	0.0					
		Deep								0.1	1.0	1.8	0.6	0.1						

2022 update: 5.8 GW scenario

			Negative ramp (GW)									Positive ramp (GW)							
			5.0	4.0	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	4.0	5.0
5.8 GW	Tech A	25 m/s						0.1	0.8	4.5	8.1	8.1	4.0	0.7	0.0					
		Moderate							0.4	2.3	4.2	4.6	2.4	0.6	0.2	0.1				
		Deep								0.3	2.5	3.1	0.9	0.2	0.1	0.0				
	Tech B	25 m/s					0.0	0.1	0.9	5.6	9.7	9.9	5.3	0.7	0.1					
		Moderate						0.1	0.4	2.5	5.0	5.5	3.0	0.7	0.2	0.0				
		Deep								0.6	2.9	3.6	1.2	0.4	0.1	0.1				

2020 report

			Negative ramp (GW)									Positive ramp (GW)							
			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
4.4 GW	Tech A	25 m/s							0.4	4.9	9.2	9.0	4.1	0.4						
		Moderate							0.0	1.1	4.1	4.5	1.4	0.1						
		Deep								0.2	2.0	2.7	0.5	0.0						
	Tech B	25 m/s							0.2	6.2	11.8	11.2	5.1	0.3	0.0					
		Moderate								1.7	5.4	5.4	1.8	0.2						
		Deep								0.2	2.5	3.2	0.8	0.1						

- **The 4.4 GW scenarios show similar extreme storm event ramps in the 2022 update and 2020 report**
  - However, the likelihoods of storm event ramps are somewhat lower in the 2022 update
    - Mainly due to the updated weather data
    - As validation with the new model is good/better than with the old model, the results are considered valid
- **The 5.8 GW scenario increases the likelihood of a high ramp compared to the 4.4 GW scenario significantly**
- **The Deep shutdown type very beneficial in the 5.8 GW scenario**

Results:
1 h ramps (#days per year, wind speed > 20 m/s)

2022 update: 4.4 GW scenario

			Negative ramp (GW)									Positive ramp (GW)								
			5.0	4.0	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	4.0	5.0
4.4 GW	Tech A	25 m/s			0.2	0.8	2.4	4.8	8.9	15	17	17	15	10	5.4	3.2	1.3	0.4	0.1	
		Moderate			0.1	0.6	1.5	3.0	6.7	13	15	16	14	8.3	3.9	2.0	1.1	0.6	0.2	
		Deep			0.0	0.2	0.5	2.0	5.8	13	15	16	13	7.4	2.6	1.2	0.6	0.4	0.1	
	Tech B	25 m/s			0.1	0.6	2.9	5.3	10	15	18	19	16	11	5.7	3.3	1.1	0.3	0.1	
		Moderate			0.1	0.7	1.7	3.5	7.3	13	16	17	14	8.4	4.0	2.3	1.3	0.5	0.1	
		Deep			0.1	0.2	0.6	2.1	6.2	13	16	17	13	7.1	2.7	1.3	0.6	0.4	0.1	

2022 update: 5.8 GW scenario

			Negative ramp (GW)									Positive ramp (GW)								
			5.0	4.0	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	4.0	5.0
5.8 GW	Tech A	25 m/s	0.0	0.5	2.5	3.8	5.6	8.4	12	17	19	19	17	13	9.1	6.2	4.5	3.0	0.8	0.2
		Moderate	0.0	0.2	1.3	2.0	3.1	5.7	9.9	15	18	18	16	11	6.6	4.0	2.7	1.9	0.9	0.2
		Deep			0.2	0.7	1.7	4.6	9.6	15	18	18	16	10	5.4	2.7	1.5	1.0	0.4	0.2
	Tech B	25 m/s	0.0	0.2	3.1	4.7	6.6	9.6	14	18	20	20	18	14	10	7.1	5.2	3.6	0.6	0.1
		Moderate	0.0	0.2	1.3	2.3	3.7	6.3	11	16	19	19	16	11	7.2	4.4	2.9	2.2	0.9	0.2
		Deep			0.3	0.8	2.2	4.8	9.9	16	19	19	16	10	5.6	2.9	1.5	1.1	0.6	0.2

2020 report

			Negative ramp (GW)									Positive ramp (GW)								
			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
4.4 GW	Tech A	25 m/s			0.1	1.0	3.4	6.1	12.1	20.7	23.9	24.2	21.5	14.1	7.8	4.0	1.9	0.5	0.2	0.1
		Moderate			0.1	0.3	1.5	3.8	9.1	18.2	22.5	22.7	19.2	11.4	5.5	2.5	1.1	0.5	0.2	0.1
		Deep			0.0	0.2	0.6	2.3	8.2	17.9	22.4	22.5	18.8	10.1	4.1	1.4	0.5	0.2	0.1	0.1
	Tech B	25 m/s			0.1	0.6	4.0	7.6	14.0	22.3	26.4	26.6	23.2	15.4	8.8	4.6	1.6	0.5	0.2	0.1
		Moderate		0.0	0.1	0.3	1.7	4.5	9.6	18.7	24.0	24.5	19.7	11.4	5.5	2.7	1.4	0.5	0.2	0.1
		Deep			0.1	0.2	0.7	2.9	8.2	18.1	23.9	24.4	19.1	9.9	3.9	1.5	0.8	0.4	0.2	0.1

- **The 4.4 GW scenarios are similar for the 2022 update and 2020 report**
- **The 5.8 GW scenario increases the likelihood of a high ramp compared to the 4.4 GW scenario significantly**
- **The Deep shutdown type highly beneficial in the 5.8 GW scenario**

Results:
Day-ahead forecast errors

2022 update

			Mean	SD	Prct 0.001	Prct 0.01	Prct 99.99	Prct 99.999	Compared to 0.9 GW SD
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%

2020 report

Table 28. Day-head forecast error statistics.

			mean	SD	Prct 0.001	Prct 0.01	Prct 99.99	Prct 99.999	Compared to BE 2018 SD
4.4 GW	Tech A	25 m/s	-0.001	0.116	-0.700	-0.618	0.601	0.775	87%
		Moderate	-0.001	0.115	-0.710	-0.618	0.581	0.680	86%
		Deep	-0.001	0.115	-0.688	-0.604	0.571	0.671	85%
	Tech B	25 m/s	-0.001	0.117	-0.697	-0.610	0.584	0.728	87%
		Moderate	-0.001	0.115	-0.694	-0.617	0.576	0.682	86%
		Deep	-0.001	0.114	-0.677	-0.605	0.569	0.673	85%

- **Similar forecast error statistics (as % of installed capacity)**
  - The most extreme percentiles slightly increased in the 2022 update
- **The other forecast horizons also show similar results**

Conclusions (and compared to the 2020 study)

- Similar **capacity factors** and standard deviation when expressed p.u.
  - Capacity factors slightly lower due to increased installations densities
- Similar **ramping characteristics** as in the 2020 report but increasing due to larger installed capacity
  - When going from 4.4 GW to the 5.8 GW scenarios (other than storm days):
    - » The frequency of ramps higher than 2.0 GW in 1 hour increases from happening on around 3-4 day a year to 10-16 days a year (for both up and down ramps)
    - » The frequency of ramps higher than 2.5 GW in 1 hour increases from happening on <1 day a year to around 3-4 days a year (for both up and down ramps)
- Similar **storm shutdown** risk characteristics during storm as in the 2020 study but increasing due to larger capacity installed
  - It is possible to lose the whole 5.8 GW (occurred in 4-6 years out of the simulated 40 years, depending on technology)
  - The frequency of negative ramps during a storm higher than 2.0 GW and 2.5 GW in 1 hour increases from happening on around 1-3 days and <1 day a year, respectively, to 2-6 days and 1-4 days a year (5.8 GW compared to the 4.4 GW scenarios)
- **Forecast errors** (as % of installed capacity) similar to the 4.4 GW scenarios in the 2020 report

Extra slides

Results:
CFs of the new sites & wake losses

2022 update

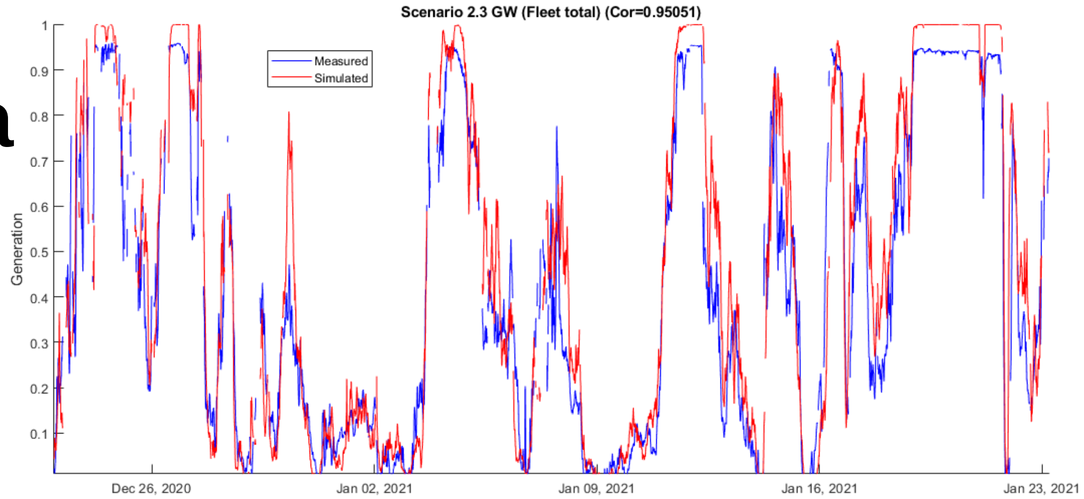
			Wake & blockage losses	CF (new sites, 100% availability)
5.8 GW (3.5 GW new installations)	Tech A	25 m/s	11.3%	0.443
		Moderate	11.2%	0.445
		Deep	11.2%	0.446
	Tech B	25 m/s	12.0%	0.503
		Moderate	12.0%	0.505
		Deep	11.9%	0.506

Report "LCOE offshore wind in the Princess Elisabeth zone", 3E, Sep 2021

Total installed capacity [MW]	Turbine type	Gross Yield [MWh]	Wake Losses [%]	Blockage Losses [%]	Total Losses [%]	Net Yield [MWh]	Net Capacity Factor [%]
3.5	17MW_Generic	17,431,015	10.9	1.0	18.1	14,283,131	46.6
	15MW_V236	18,446,761	11.6	1.1	18.8	14,972,322	48.8
	13MW_Haliade-X	18,085,074	12.3	1.1	19.5	14,560,398	47.5

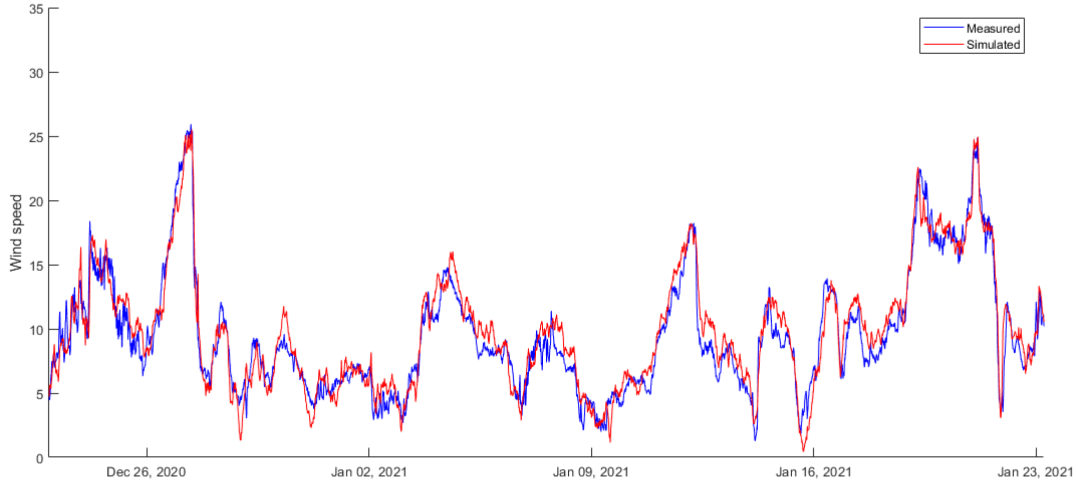
- **DTU's analyses are well aligned with the "LCOE offshore wind in the Princess Elisabeth zone" report**
- Wake (& blockage) losses of the "17MW_Generic" type are closest to the DTU's analyses
    - Makes sense as it is closest in size to the turbines in the DTU's runs

Update of model validation: Correlation to measured data



Scenario 2.3 GW:

- Correlation between measured and simulated data: **0.95**
  - Fleet-level time series
  - 5 min resolution



Results:
1 h ramps (#days per year)

2022 update: 4.4 GW scenario

			Negative ramp (GW)									Positive ramp (GW)								
			5.0	4.0	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	4.0	5.0
4.4 GW	Tech A	25 m/s			0.2	0.9	3.8	16	84	257	313	311	256	91	20	6.0	2.0	0.6	0.1	
		Moderate			0.1	0.6	2.9	14	82	255	312	310	254	89	18	4.8	1.8	0.7	0.2	
		Deep			0.1	0.2	1.9	13	81	255	312	310	254	88	17	4.0	1.3	0.5	0.1	
	Tech B	25 m/s			0.1	0.8	5.0	20	96	261	315	313	260	98	22	5.8	1.7	0.4	0.1	
		Moderate			0.1	0.9	3.8	18	93	259	313	311	257	96	20	4.8	1.8	0.6	0.1	
		Deep			0.1	0.4	2.7	17	92	258	313	311	257	94	19	3.9	1.2	0.5	0.1	

2022 update: 5.8 GW scenario

			Negative ramp (GW)									Positive ramp (GW)								
			5.0	4.0	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	4.0	5.0
5.8 GW	Tech A	25 m/s	0.0	0.6	2.8	6.0	15	52	160	291	328	327	291	165	58	19	8.4	4.2	0.9	0.2
		Moderate	0.0	0.2	1.6	4.2	13	49	158	289	327	326	289	162	56	17	6.6	3.1	1.0	0.2
		Deep		0.1	0.5	2.9	11	48	157	289	327	326	289	161	54	16	5.5	2.2	0.5	0.2
	Tech B	25 m/s	0.0	0.3	3.7	8.1	20	63	175	293	328	328	292	178	67	24	9.3	4.7	0.7	0.1
		Moderate	0.0	0.2	1.9	5.7	17	59	172	291	327	326	290	175	64	21	7.1	3.3	1.0	0.2
		Deep		0.1	1.0	4.2	15	58	171	291	326	326	290	174	63	19	5.7	2.2	0.7	0.2

2020 report

			Negative ramp (GW)									Positive ramp (GW)								
			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
4.4 GW	Tech A	25 m/s			0.2	1.6	6.3	21.9	105.4	282.8	328.1	325.7	282.5	118.1	30.4	8.6	3.0	0.7	0.2	0.1
		Moderate			0.2	0.9	4.4	19.6	102.3	280.4	326.6	324.1	280.2	115.4	28.0	7.1	2.2	0.6	0.2	0.1
		Deep			0.2	0.8	3.5	18.1	101.4	280.1	326.6	323.9	279.9	114.2	26.6	6.0	1.6	0.3	0.1	0.1
	Tech B	25 m/s			0.2	1.4	7.5	26.7	114.2	286.7	330.9	329.8	288.4	121.7	32.1	8.9	2.5	0.6	0.2	0.1
		Moderate		0.0	0.2	1.0	5.1	23.6	109.8	283.0	328.5	327.6	284.7	117.6	28.7	6.9	2.2	0.7	0.2	0.1
		Deep			0.2	1.0	4.1	22.0	108.3	282.4	328.5	327.4	284.1	116.1	27.0	5.7	1.6	0.5	0.2	0.1

Results:
5 min ramps (#days per year, all wind speeds)

2022 update: 4.4 GW scenario

			Negative ramp (GW)									Positive ramp (GW)								
			5.0	4.0	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	4.0	5.0
4.4 GW	Tech A	25 m/s							0.3	3.0	13	14	2.9	0.5	0.0					
		Moderate							0.1	1.7	11	12	2.0	0.2	0.0					
		Deep								0.7	8	10	1.2	0.1	0.0					
	Tech B	25 m/s							0.4	3.5	16	16	3.1	0.4	0.0					
		Moderate							0.1	2.5	13	13	2.7	0.3	0.0					
		Deep								1.0	11	12	1.5	0.1						

2022 update: 5.8 GW scenario

			Negative ramp (GW)									Positive ramp (GW)								
			5.0	4.0	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	4.0	5.0
5.8 GW	Tech A	25 m/s						0.1	0.8	7.0	30	32	6.0	0.7	0.0					
		Moderate							0.4	4.7	26	28	4.3	0.6	0.2	0.1				
		Deep								2.7	24	27	2.7	0.2	0.1	0.0				
	Tech B	25 m/s					0.0	0.1	0.9	8.6	39	41	8.0	0.7	0.1					
		Moderate						0.1	0.4	5.4	34	36	5.7	0.7	0.2	0.0				
		Deep							0.1	3.5	32	34	3.8	0.4	0.1	0.1				

2020 report

			Negative ramp (GW)									Positive ramp (GW)								
			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
4.4 GW	Tech A	25 m/s							0.4	5.9	19.1	19.1	5.1	0.4						
		Moderate							0.0	1.3	13.2	13.9	1.8	0.1						
		Deep								0.5	11.0	12.1	0.9	0.0						
	Tech B	25 m/s							0.3	7.5	24.3	23.6	6.3	0.3	0.0					
		Moderate								2.2	17.1	16.9	2.3	0.2						
		Deep								0.7	14.1	14.6	1.2	0.1						

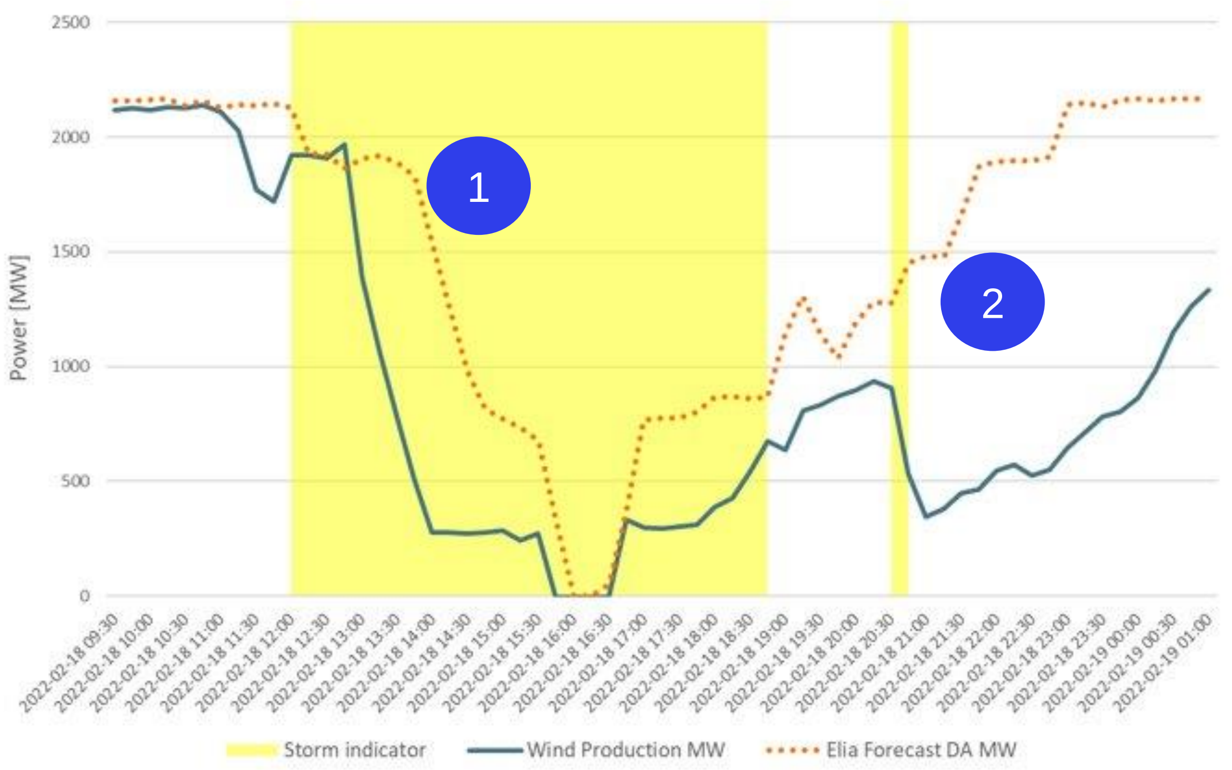
Is it realistic that we see the complete fleet in storm shutdown?

- Happened for the 2.3 GW scenario during storm Eunice:

Event description – Storm Eunice (18-19 Feb. 2022)

1 Wind power generation faced a full cut-out in about 5 hours. The full cut out was predicted by Elia's forecast tool.

2 Note that the wind power generation also faced an unexpected partial cut-out during recovery phase.



Methodology for the impact assessment on balancing and system integration during

A. Normal conditions : impact on reserve capacity needs

Presented by Kristof De Vos

Methodology to determine impact on Elia's reserve needs

A. Analyze future offshore generation profiles

B. Determine impact on system flexibility needs

C. Determine impact on Elia's reserve needs

D. Determine impact on real-time system operation

E. Analyze potential mitigation measures

Scenario's on future BRP ability to balance portfolios

- Ability of BRPs to balance forecast errors of additional RES installed
- LFC block imbalance quality
- Forecast tool improvements

Projections of future system imbalances

- Upscaling of historic LFC block imbalances towards 2028
- Upscaling forced outages & prediction risks
- Time series of offshore generation of DTU

Estimations of future balancing capacity needs

- Estimations of the future FRR/aFRR/mFRR needs
- Estimation on the dynamic dimensioning behavior

Potential impact of bidding zones

Under current European legislation, the creation of a separate Offshore LFC Area within the Elia LFC block seems at this point the best way forward (cf. next presentation)

- Seems to facilitate a joint dimensioning, minimizing reserve capacity needs for both areas
- Seems to avoid fundamental impact on the reserve dimensioning method and corresponding projections
- Specific attention seems needed for downward flexibility during high Belgian import conditions

Cf. further discussions during next presentation and workshops

Methodology for the impact assessment on balancing and system integration during

B. Exceptional conditions : impact of storms and ramps on system operation

Presented by Aymen Chaouachi

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Overview, scope and context

Context :

- Change of OWF installed capacity from **4.4 GW to 5.8 GW**
- **Future evolutions** Energy Island, new connections and offshore bidding zones

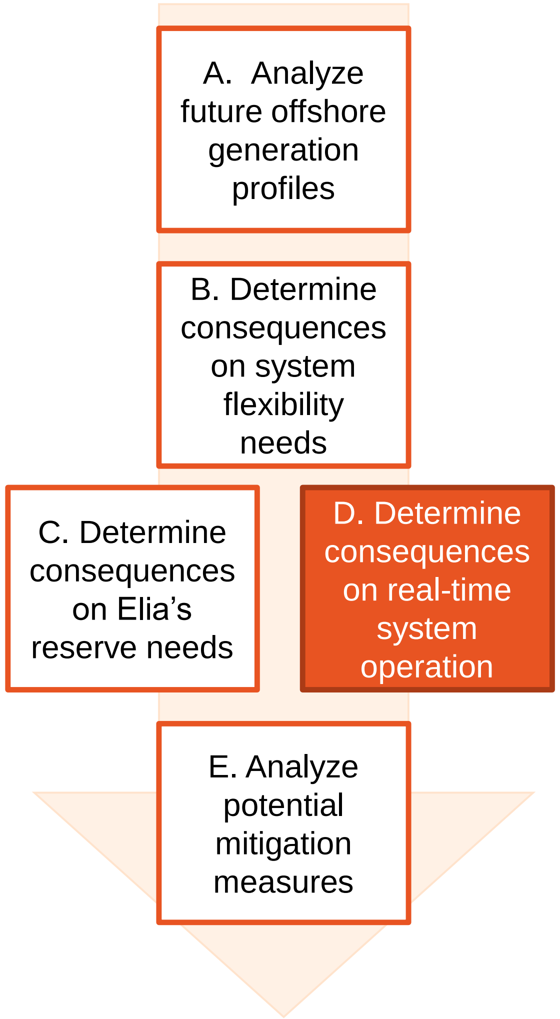
Objective **:**

- **Update MOG 2** System Study: **Impact** and effectiveness of **mitigation measures**

Scope**:**

- Update **simulation analysis** cover ramping up/down and storms events from DTU study
- Assess impact on FRCE considering **sensitivities and mitigation criteria**

Overview on impact assessment



- Select representative events to cover the worst cases of
  - extreme up and down **ramp** events
  - **storm** events
- Methodology to evaluate impact on real-time balancing operations

Define System assumptions :

- Expected **BRP coverage**
- **Available** FRR reserve capacity
- Elia reserves **Activations** (sensitivity analysis)

Simulate the impact on real-time balancing operations for each scenario

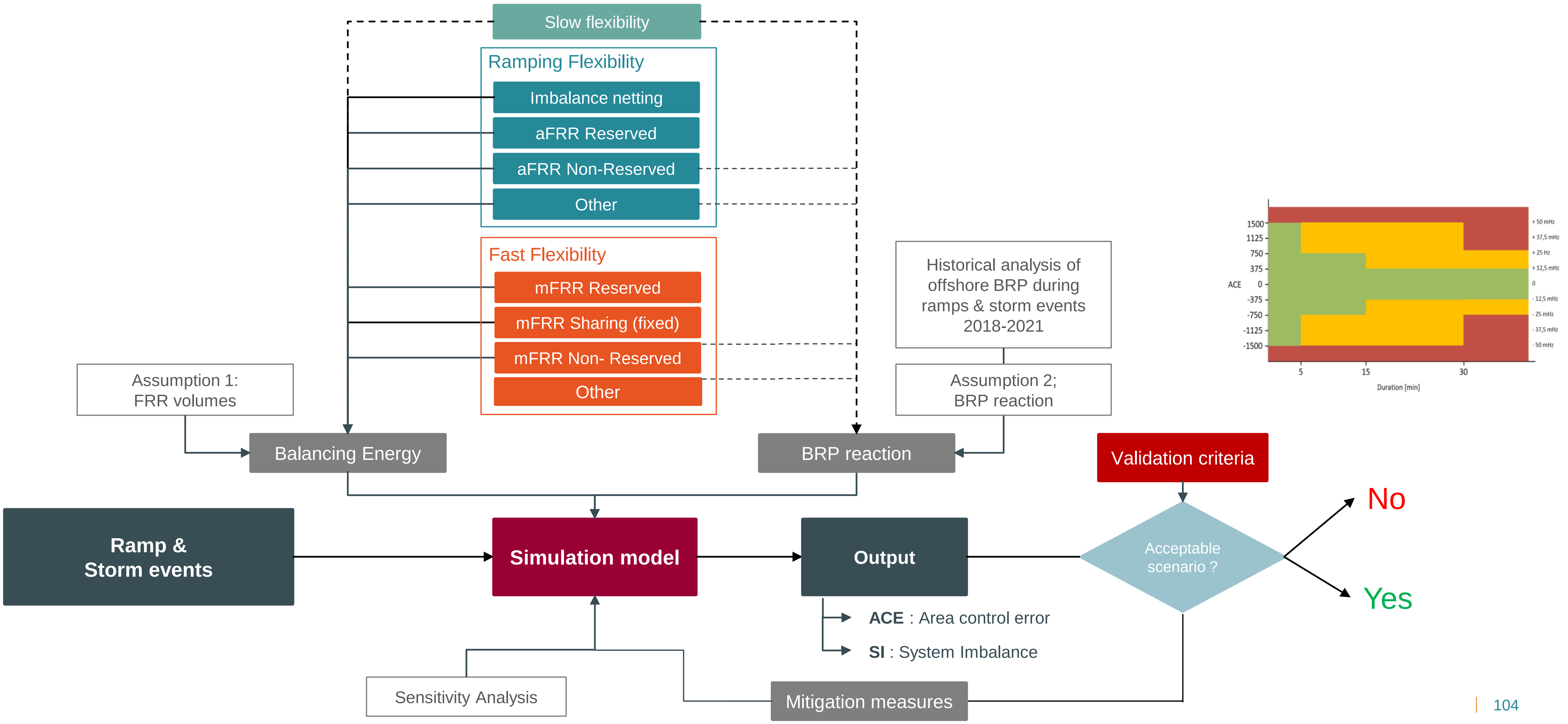
- **Size** of possible imbalance
- **Duration** of possible imbalance

-> Degree of violation

⇒ Draw up conclusions on the need for mitigation measures.

Methodology

Simulation Model



Methodology key updates

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- **aFRR controller is tuned** to larger aFRR activation volumes
- 5 min FAT for all **aFRR reserves activation**, using Merit Order List activation sequence as per PICASSO design
- Improvement of **mFRR activation logic** to capture better operator decisions (D/S activations) following MARI design
- Improvement of modelling dependence between frequency and system imbalance.

- Study is based on system imbalances and area control errors resulting from offshore wind (compensated by assumptions on available flexibility)
  - No fundamental impact on the model when considering an offshore bidding zone
- Uncertainty on available reserve capacity, BRP ability and topology evolution are captured through sensitivity analysis
- There is no impact assumed on system imbalance if wind power is connected through DC or AC

Thank you