FarmConners Market Showcases

Sep 05, 2022

Contents

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First, here is a *quick summary* for those eager to get started!

Wind farms are currently operated with the primary control objective to maximise power generation. As the penetration of wind energy rises, this strategy may no longer be feasible, especially if government subsidies are reduced. In such a scenario, wind farm flow control (WFFC) can offer wind farm operators additional flexibility to maximise profits. For example, if electricity prices fall operators could curtail power generation in favour of load reduction strategies. To date, the lack of convincing evidence for the economic case for WFFC has prevented its widespread adoption.

The FarmConners project launches a set of showcases that researchers within the WFFC community can use to assess the positive impact of their control strategies. These showcases are based on the TotalControl Reference Wind Power Plant with weather simulation data and estimated electricity prices for both 2020 and 2030, provided courtesy of the DTU Balancing Tool Chain. With this data, researchers can evaluate the performance of their control algorithms using an internationally recognised tool.

The showcases repository is located here.

All showcases participants will be involved in the final publication, where the comparison of different WFFC strategies will be performed using the defined showcases. Instructions on how to participate are provided on *How to Participate*. The deadline is November 2021.

This documentation is based on the paper "FarmConners market showcases for wind farm flow control" by Kölle et al. (2020) that was presented at the 19th Wind Integration Workshop and published in the workshop's proceedings.

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CHAPTER 1

Content

1.1 In Short

1.1.1 What?

The FarmConners Market Showcases are basically:

- Datasets of electricity prices and inflow (wind speed and direction)
- To be used as input to wind farm control (WFC)
- When simulating a reference wind farm

1.1.2 Why?

Some (of all the good) reasons why you should participate are:

- Relative evaluation of your tool/approach together with others
- Revenue estimation for your tool/approach which could be handy when applying for future projects
- Co-authorship of the resulting FarmConners paper
- Your own publication about details of implementation and results
- Collaboration with researchers at leading European institutions in the field of wind farm control
- Supporting the advancement of wind farm control
- It is fun

1.1.3 How?

1. Register *here*
2. Set up the *reference wind farm* (or the simplified version) in your simulation tool

3. Run a simulation without WFC using the showcases data as input (nominal case)
4. Run a simulation with WFC using the showcases data as input
5. Submit your results

At any time, *contact us* if you have questions.

1.1.4 Data format

The data is provided in CSV files.

- **Binned data for the *Market Showcases* with 1. high electricity prices and 2. low electricity prices is organized like**

Wind direction bin center	Wind Speed bin center	WS Hub-Height mean	WS 50m mean	WS 80m mean	WS 100m mean	WS 150m mean	Wdir Hub-Height mean	Wdir 50m mean	Wdir 80m mean	Wdir 100m mean

Wdir 150m mean	Ustar Hub-Height mean	Ustar 50m mean	Ustar 80m mean	Ustar 100m mean	Ustar 150m mean	TI Hub-Height mean	DA 2020 mean

- **Data for the TSO-driven *Market Showcase* is organized like**

WS Hub-Height	WS 50m	WS 80m	WS 100m	WS 150m	Wdir Hub-Height	Wdir 50m	Wdir 80m	Wdir 100m	Wdir 150m	Ustar Hub-Height	Ustar 50m	Ustar 80m	Ustar 100m	Ustar 150m	TI Hub-Height

1.1.5 Inspiration?

Here are some examples of implementation/workflow for different tools.

<table>
<tr><th>For power objectives</th><th>For power & load objectives</th></tr>
<tr><td>

- **Low Cost WF Setup** Steady-state tools (FLORIS, Fuga, etc.)

</td><td>

- **Medium Fidelity/Cost WF Setup** FAST.Farm or similar

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- **Simulations for ‘bins’ & control settings for**
  - Wind speed bin center $\pm 1m/s$
  - Wind direction center $\pm 15°$
  - **Control settings per turbine**
    - Steering: $0°$: $-5°$: $-35°$
    - Down-regulation: 5%: 5%: 30%
    - Combinations!

</td><td>

- **Simulations for chosen ‘bins’ & control settings for**
  - Wind speed bin center $\pm 1m/s$
  - Wind direction center $\pm 15°$
  - **Control settings per turbine**
    - Steering: $0°$: $-5°$: $-35°$
    - Down-regulation: 0%, 5%: 5%: 30%
    - 20-min runs
- Build a surrogate

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- **Optimize for**
  - High-price -> revenue increase

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- **Optimize for**
  - High-price -> revenue increase
  - Low-price -> load alleviation
  - TSO-driven -> load alleviation

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1.2 Introduction

The more capacity of wind power that is commissioned and the larger wind farms grow, the more relevant the integration of intermittent wind power into the power system becomes. In the future, a Wind Farm (WF) will need to act more like a conventional power plant, *i.e.* complying to stricter grid code requirements and providing ancillary services to ensure safe and reliable operation of the power system. Furthermore, the role of wind power in the electricity markets will likely change, increasingly exposing WFs to the volatility of wholesale electricity prices (Hu et al., 2018). The traditional primal objective of maximising the Annual Energy Production (AEP) is expected to shift to maximising the overall profit instead.

Improved and more coordinated Wind Farm Control (WFC) has the potential to create the flexibility for WFs to participate in electricity markets to a larger extent than today. Balancing power production, load reduction and ancillary service provision will be necessary to maximise WF revenue in the future, while supporting the local grid. For example, curtailing the power generation during periods with low electricity prices, can provide incentives to follow secondary farm control objectives such as reducing structural loads or noise. This can be accomplished through Wind Farm Flow Control (WFFC), where wakes induced by upwind turbines are manipulated to reduce the impact on downwind turbines.

In this way, WFC, in its broadest sense, means the coordinated operation of the different wind turbines within a wind farm to serve a common goal. Within this paper, WFFC refers to the coordination of the actions of individual turbines in a farm for the purpose of improving inter-turbine aerodynamic interaction, to better the overall farm power production and/or reduce or distribute the structural loading among wind turbines. As such, WFFC forms part of the overall WFC strategy along with ancillary service provision, power quality management among other control modes.

In 2019, the European research project FarmConners <https://www.windfarmcontrol.info/>‘_ was started with the main goal of providing an overview of the state of the art in wind farm control, identifying consensus of research findings, data sets and best practices, providing a summary of the main research challenges, and establishing a road map on how to address these challenges. One of the challenges identified to the widespread adoption of WFFC was evidence of the positive economic impact that it offers. As such, as part of the FarmConners project, a number of market scenarios have been developed as showcases to allow researchers to evaluate their WFFC strategies against a common baseline to demonstrate the potential benefits of WFFC. This paper introduces these showcases, detailing how they have been developed.

The TotalControl Reference Wind Power Plant (TC-RWP) has been chosen as an example of a large wind farm which may benefit the most from altering their operation based on the electricity markets.

The focus of the showcases lies on the operational phase, *i.e.* the influence of auction prices and practices as well as the design phase and commissioning are disregarded. The showcases are based on a time series of weather simulations and estimated electricity prices for 2020 and 2030 generated using the DTU Balancing Tool Chain. The weather simulations for the chosen location of the TC-RWP are run using data from 2012. The North Sea region is included in the energy systems modelling, and hourly day-ahead prices in the relevant Danish price region (DK1) are obtained. These market prices are used as fixed inputs for the analysed wind farm in the showcases. The 2020 and 2030 scenarios are both based on the same weather data but are coupled with different energy systems representing the composition in 2020 and 2030 (electric loads, CO2 price, installed generation capacities, etc.).

The showcases consist of three sets: 1) High electricity prices, 2) Low electricity prices, 3) Operation driven by the system operator. Depending on the showcase set, income, reference tracking and load alleviation will be used as performance indicators and compared to the nominal operation without WFFC. Participation in the public showcase study is open for all academic and industrial experts. Every participant will be involved in the final publication which will demonstrate the performance of different WFFC tools in the defined showcases. Instructions on how to participate are provided on *How to Participate*.

The market showcases provide (future) scenarios in which WFFC should or can contribute to ensure feasible participation of WFs in relevant markets, such as intraday or balancing markets. The developed showcases serve to evaluate the potential benefits of WFFC.

1.3 Reference Wind Farm

The showcases are defined for a reference wind farm at an exemplary offshore location. An offshore WF is used because the market influence may be more pronounced for larger wind farms such as those installed offshore.

The TotalControl Reference Wind Power Plant (TC-RWP) with publicly available specifications was chosen as the reference WF. The TC-RWP consists of 32 10 MW wind turbines in a staggered layout.

The simulations assume that the TC-RWP is located approximately 20 km west of the Danish wind farm Horns Rev. Denmark is chosen as the reference location due to the already high share of wind power in the Danish power system. This ensures that changing wind conditions have a more realistic effect on the electricity price in the simulated *Scenarios*. Due to its location, the reference WF is part of the power system in West Denmark (referred to as *DK1* here).

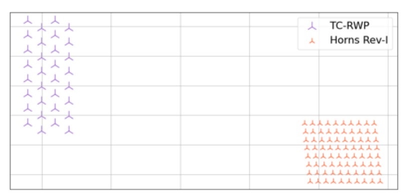


Fig. 1: Layout of the Total Control Reference Wind Power Plant (TC-RWP) and location in the FarmConners Market Showcases.

1.3.1 Simplified farm layout

computational limitations may restrict you to simulate the whole reference wind farm with 32 turbines. In this case, you may use the subset of the TC-RWP as indicated in the figure. Please indicate this also when *registering*.

If you would prefer a further simplified layout, please *contact us*.

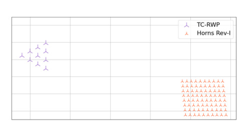


Fig. 2: Subset of the TC-RWP.

1.4 Scenarios

In order to identify, develop and validate wind farm control strategies for future power and energy systems, it is important to model the future energy market, operation and scenarios. Future energy scenarios are simulated as investment optimisation for 2020 and 2030 based on Koivisto et al. (2019b), the NSON report on enery system scenarios, and the NSON report on day ahead market operation.

Meteorological year data from 2012 is used for these simulations. The scenarios are based on an investment optimisation of the generation and transmission capacity for North Sea countries. Scenarios with both radial offshore connections of WFs to the grid as well as meshed offshore grids are considered in the investment optimisation. However, only the scenarios with radial connections are included in the FarmConners market showcases. The resulting transmission lines in the North Sea region for 2030 are depicted in the figure on the right. As shown, the level of interconnection between the studied countries is high, especially to Norway. Connections with Norway proved to be crucial in the simulations where Norwegian hydro power was not only used to cover the domestic demand, but also to provide flexibility to its neighbours. More details are provided in the NSON report on enery system scenarios.

DTU Wind has developed the DTU Balancing Tool Chain consisting of CorRES, OptiSpot, OptiBal, and Area and Frequency control model to analyse market and balancing operation in future energy scenarios (Das et al., 2020, NSON report on balancing tool chain).

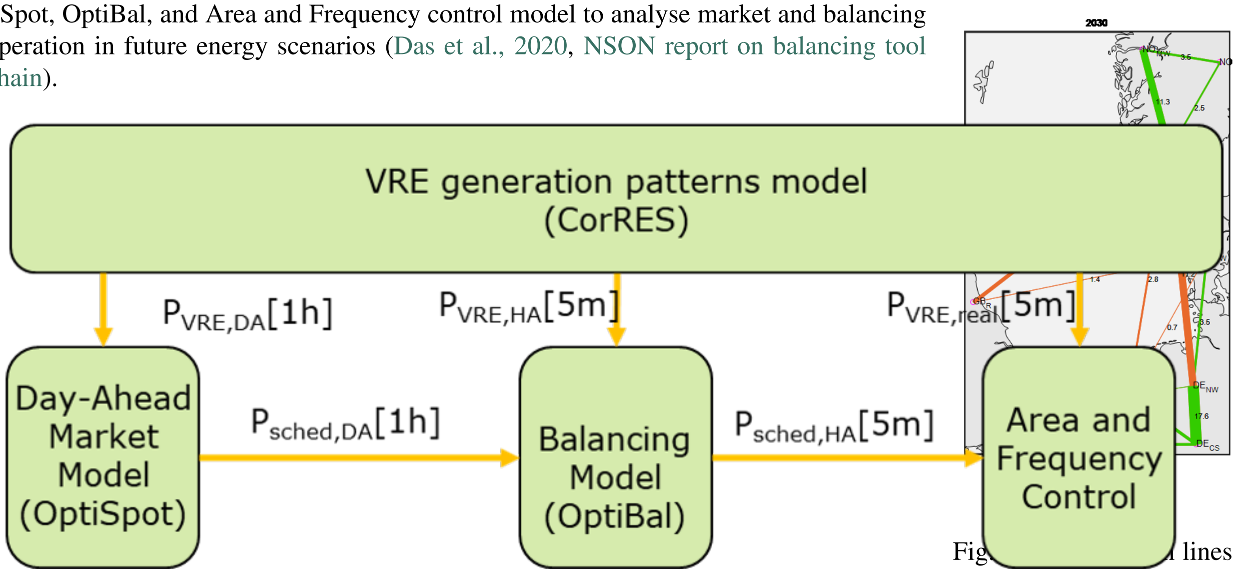


Fig... lines in 2030 (GW) (Koivisto et al., 2019b): Onshore lines in green and country-to-country offshore lines in orange.

Simulating the large power systems does not only include unit commitment but also operational planning constraints such as yearly hydro scheduling, scheduled maintenance, and heating constraints (NSON report on day ahead market operation). The scenario simulations include different generators of Variable Renewable Energy (VRE), but only wind power is considered here. All wind power generation is aggregated at the market area level and considered as price maker. The spot market practices are assumed to remain similar to today. It has been observed that wind power plays a major role in dictating the electricity prices mainly in the 2030 scenario when the share of renewable energy is high. The FarmConners market showcases use the obtained price signals as an input for WFFC, where the reference wind farm acts as price taker. It is assumed that each WF is acting on its own, without coordination of several farms having the same owner. As mentioned earlier, the electricity price signal for DK1 is considered for the showcases.

Balancing principles followed by the Danish Transmission System Operator (TSO), Energinet, are implemented for the considered scenarios, to simulate the volume of up-regulated and down-regulated power, as well as the prices for up-regulation and down-regulation (NSON report on the balancing tool chain).

In future, the wind farms are expected to act mainly on spot and balancing market prices. However, external signals from the TSO are sometimes obtained in lieu of disturbances/congestion in the power system. As per today's practice, these signals can be converted into different control modes such as delta control, balance control, ramp rate limitation (Hansen et al., 2006). These situations are considered as TSO-driven cases in the *Market Showcases*.

The steps of the scenario simulations can be summarised as: 1. CorRES simulates an hourly time series for the aggregate Variable Renewable Energy (VRE) generation sources in each analysed European region. The simulations include time series for day-ahead (DA) power forecast ($P_{\mathrm{RES,DA}}$), hourly-ahead (HA) power forecast ($P_{\mathrm{RES,HA}}$) and available power ($P_{\mathrm{RES,real}}$). 1. OptiSpot, which is implemented in Balmorel, uses the DA forecast from CorRES ($P_{\mathrm{RES,DA}}$) to simulate the unit commitment and schedules the hourly behaviour of the entire power system in the DA spot market ($P_{\mathrm{sched,DA}}$). This results in hourly DA prices for each region as well as power plans from different generators of which only wind power is used in the showcases. 1. The OptiBal HA runs (also implemented in Balmorel) are based on the DA market plans ($P_{\mathrm{sched,DA}}$) and updated HA forecast ($P_{\mathrm{RES,HA}}$) to mitigate the imbalance prognosticated in each control area. This results in simulated balancing prices and regulating power in each control area ($P_{\mathrm{plan,HA}}$). 1. CorRES is also used to simulate plant-level weather data at the location of the reference WF. Wind speeds are available in 5 min resolution.

The area and frequency control model of the DTU Balancing Tool Chain is not part for the scenario simulations that are part of the FarmConners market showcases.

1.4.1 Simulation of aggregate and plant-level VRE in CorRES

The VRE time series simulations for the scenarios are carried out using the DTU Correlations in Renewable Energy Sources (CorRES) simulation tool (Koivisto et al., 2019). CorRES simulations are based on the meteorological data described in Nuno et al. (2018). With pan-European coverage, the weather data provides aggregate (country-level or regional level) time series for the large-scale energy system modelling. The Balmorel energy system model (Wiese et al., 2018) is used for the scenarios presented in this paper; the framework of using CorRES and Balmorel is described in (Gea-Bermudez et al., 2020).

In addition to the aggregate time series presented in the following sections, CorRES is used to give weather data for the reference WF. These weather time series are correlated with the aggregate time series (e.g., DA prices), because they are an output of the same underlying weather data. The weather data represents the average value for the central point of the TC-RWP.

Wind variations may be smoothed because of spatial and temporal averaging effects in mesoscale models (Larsén et al., 2012). Thus, the stochastic simulation part of CorRES is utilised (Koivisto et al., 2020). Adding the fluctuations provides more realistic variability, and allows sub-hourly simulation of the plant-level wind speeds. Wind speeds with a resolution of 5 min are simulated for the reference WF. Since wind direction variations remain hourly however, showcase results are assumed to represent an upper bound of attainable benefits.

Simulated wind speed and direction for the reference WF are shown in the above figure for the selected weather data year of 2012. Due to its relevance for WFFC with its high thrust, hence stronger wake effects, the wind speed region of 6 – 12 m/s will be considered for the showcases. The corresponding wind rose for that region, including the frequency of occurrence within the meteorological year shows that the majority of the inflow data included in the showcases is from westerly directions, providing opportunities to investigate the market benefits of WFFC for turbines with cross-wind distances (not fully aligned to the flow).

1.4.2 Simulation of day-ahead markets using OptiSpot

Simulations of the day-ahead market are performed using OptiSpot in Balmorel. The simulated day-ahead prices in EUR for DK1 in 2020 and 2030 are presented in the figures above. The prices are given at the price level of 2012 because the considered meteorological data is from 2012. It can be observed that the prices vary from approximately 0 EUR/MWh to 40 EUR/MWh in 2020 and to more than 100 EUR/MWh in 2030. This provides justification to

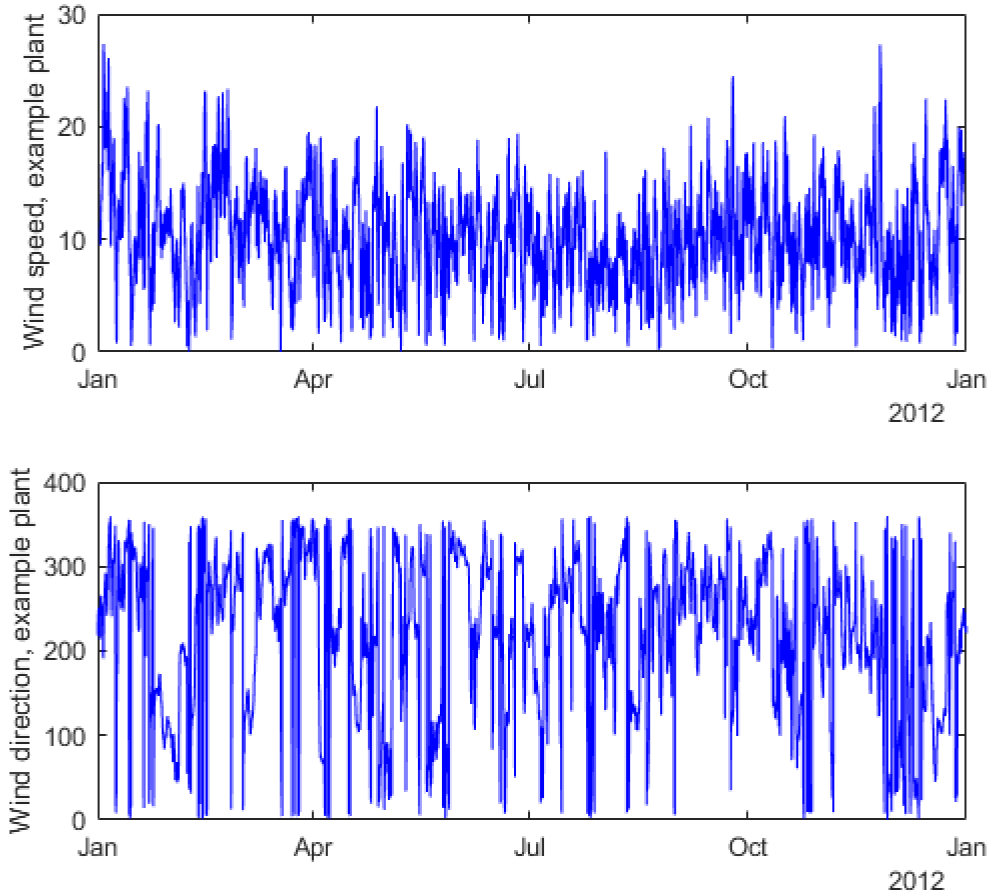


Fig. 4: Simulated wind speed and direction at the location of the reference WF.

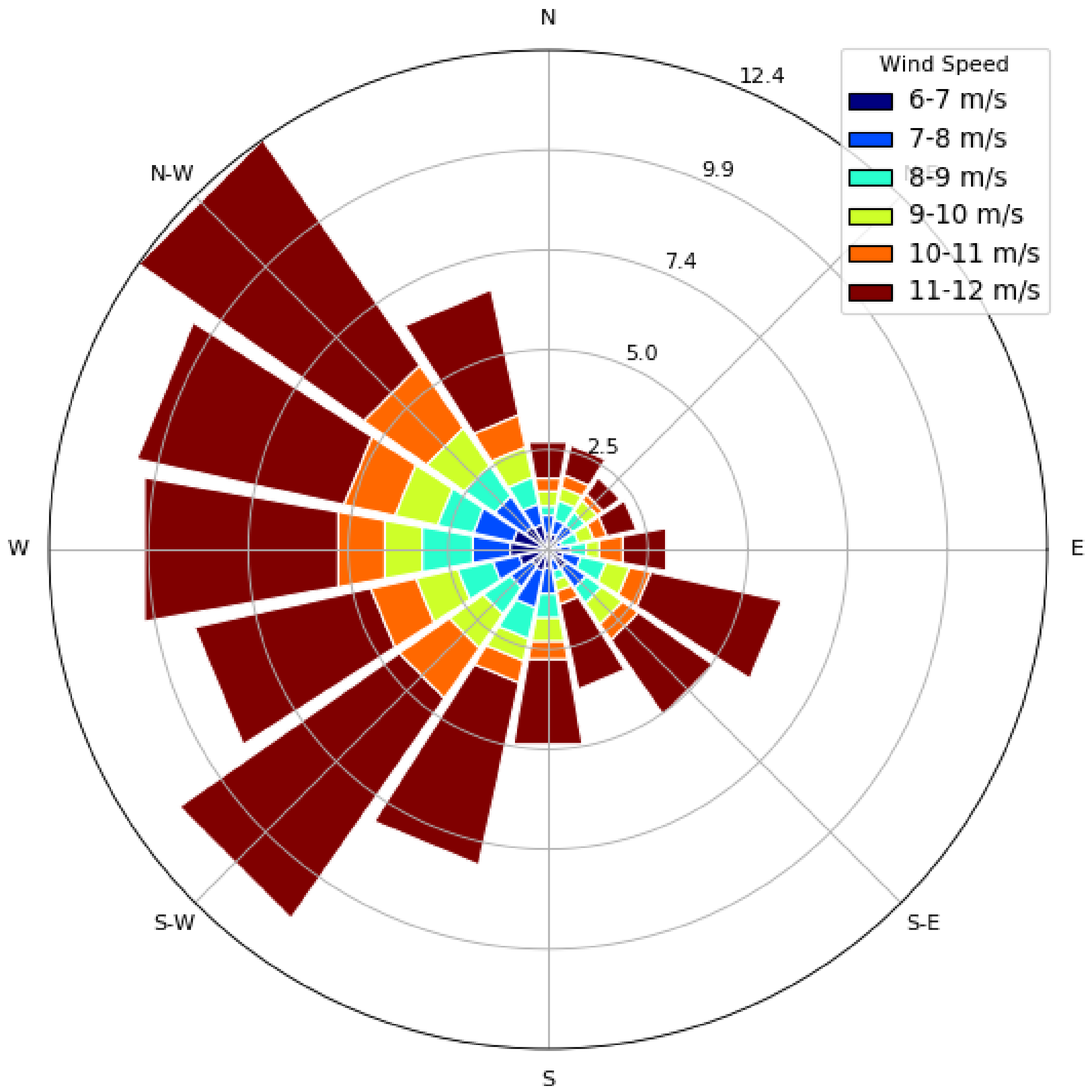
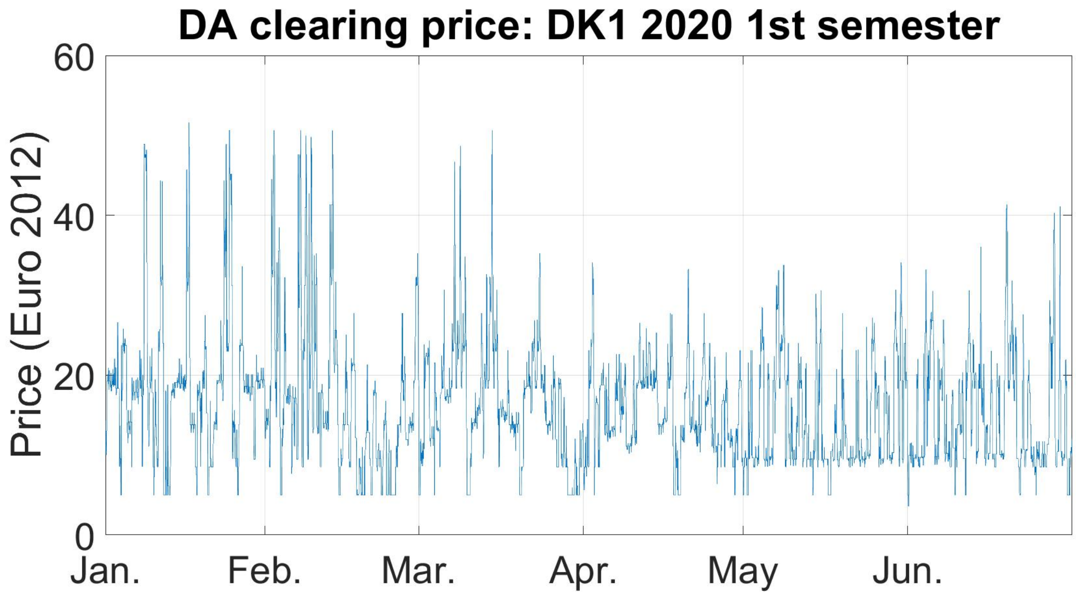


Fig. 5: Wind rose, filtered for the wind speed region of interest, at the reference WF.



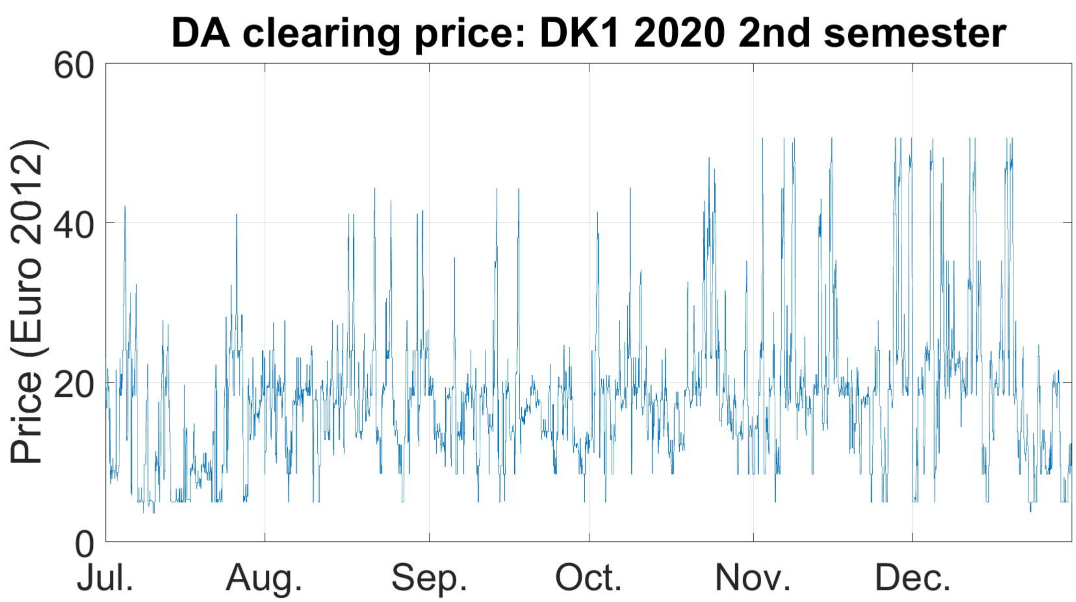
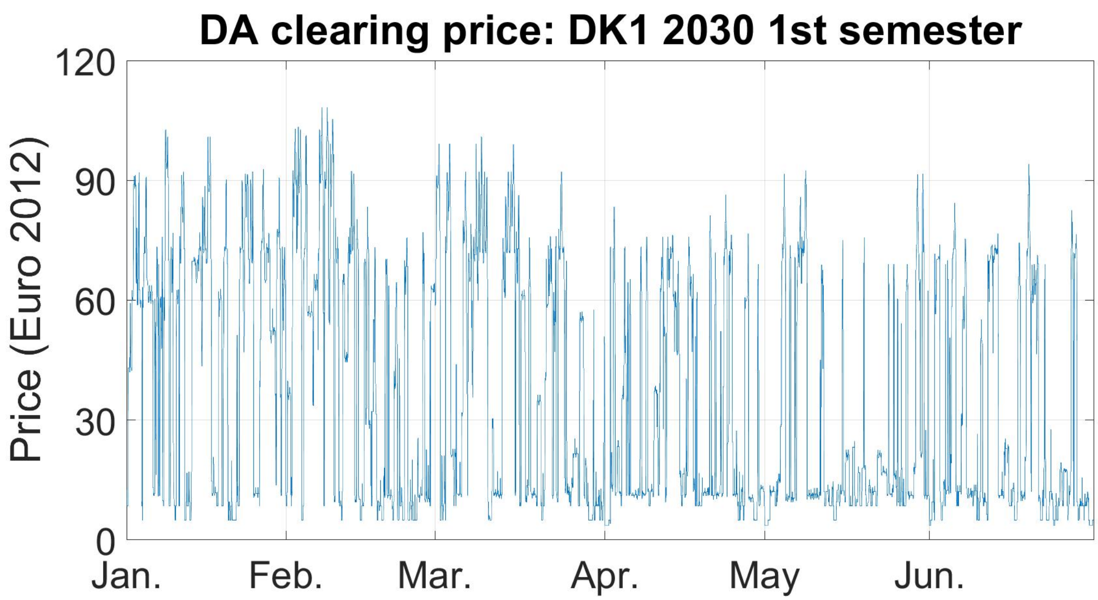


Fig. 6: Simulated day-ahead (DA) clearing price time series for the DK1 region in 2020. Prices are in EUR 2012 value since the considered meteorological data is from 2012.



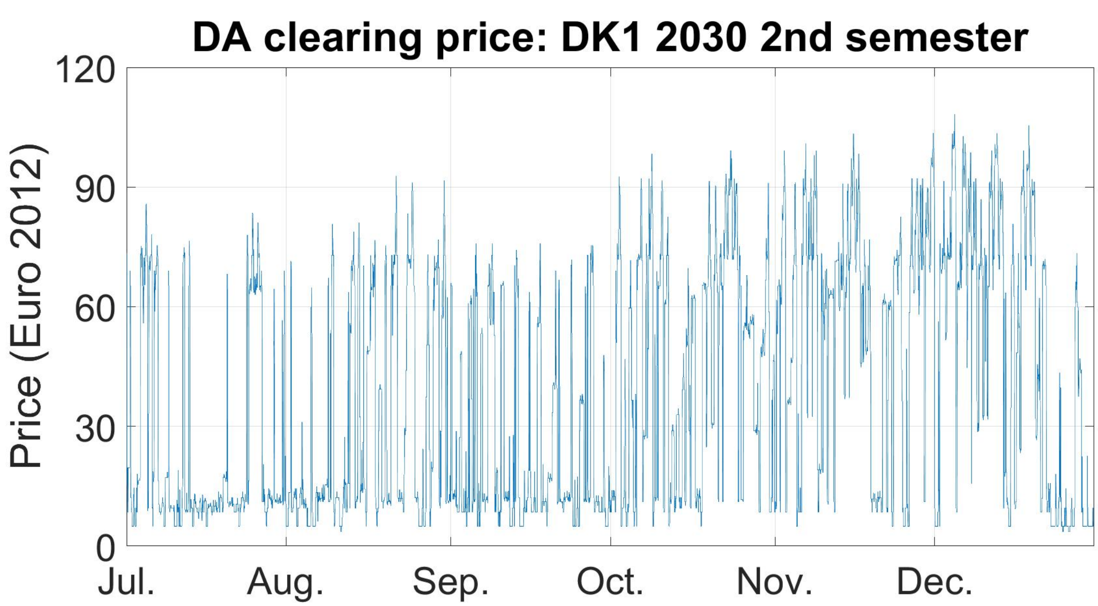


Fig. 7: Simulated day-ahead (DA) clearing price time series for the DK1 region in 2030. Prices are in EUR 2012 value since the considered meteorological data is from 2012.

control the WF towards maximising revenue from market instead of only maximising energy production. In order to understand the variability of the prices, duration curves for 2020 and 2030 prices are plotted in the Figure below. It illustrates that the electricity price increases and becomes more volatile from 2020 to 2030. This development is caused by the link between the electricity prices and the fees for CO_2 emissions. It is assumed that fossil fuels will still account for a considerable part of the electrical power in 2030 and since the CO_2 price is increasing, electricity prices expand too, resulting in an increased variability of spot market prices.

It is interesting that the price is below 20 EUR 50% of the time, while the price is above 60 EUR for 40% of the time.

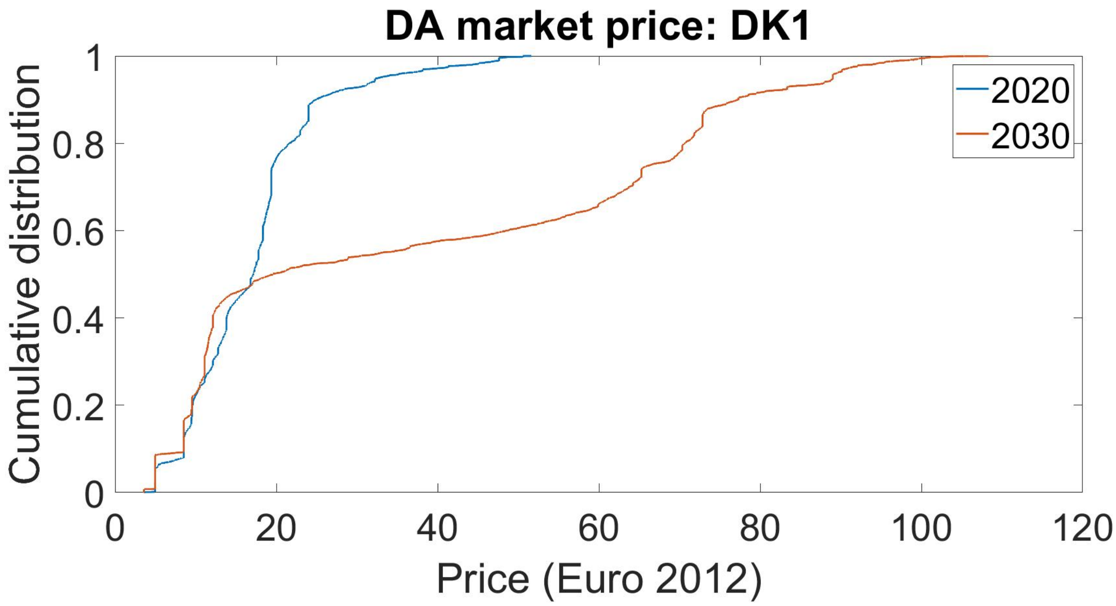


Fig. 8: Cumulative distribution of the simulated day-ahead (DA) market clearing price for DK1 region in 2020 and 2030. Prices are in EUR 2012 value since the considered meteorological data is from 2012.

1.4.3 Simulation of balancing markets using OptiBal

Simulations in OptiBal are used to discuss the potential participation of wind farms in future balancing markets. Hour-ahead imbalances for DK1 are calculated as the differences between DA plan $P_{sched,DA}$ and HA forecast $P_{RES,HA}$ of wind power. From the figures above, it can be clearly observed that extreme imbalances (the tails of the probability density functions) increase substantially in the 2030 scenario. This can signify that in the future, when there are few hours with high HA imbalances, WFs might need to play a major role in balancing processes.

In general, the volume of the imbalances is increasing towards 2030 following the increased share of energy generated from wind, which certainly demonstrates the potential of WFC to earn revenue from balancing market.

During the hour-ahead balancing market, wind generation forecast simulations (which are more accurate than day-ahead) are taken into consideration and thus the day-ahead dispatch schedule is adapted. The generators participating in balancing need to regulate their dispatch level up or down depending on the instantaneous imbalance in the system. The resulting cumulative prices can be seen from the figures above. The prices for up-regulation and down-regulation are substantially increasing, and their volatility is higher in 2030 as compared to 2020.

The simulation procedure to generate the time series for up-regulation and down-regulation prices is as follows:

- **Up-regulation: If the WF is already curtailed in DA dispatch, it is possible to up-regulate**
    1. Estimation of up-regulation prices
    2. Potential amount/volume of up-regulation in MW

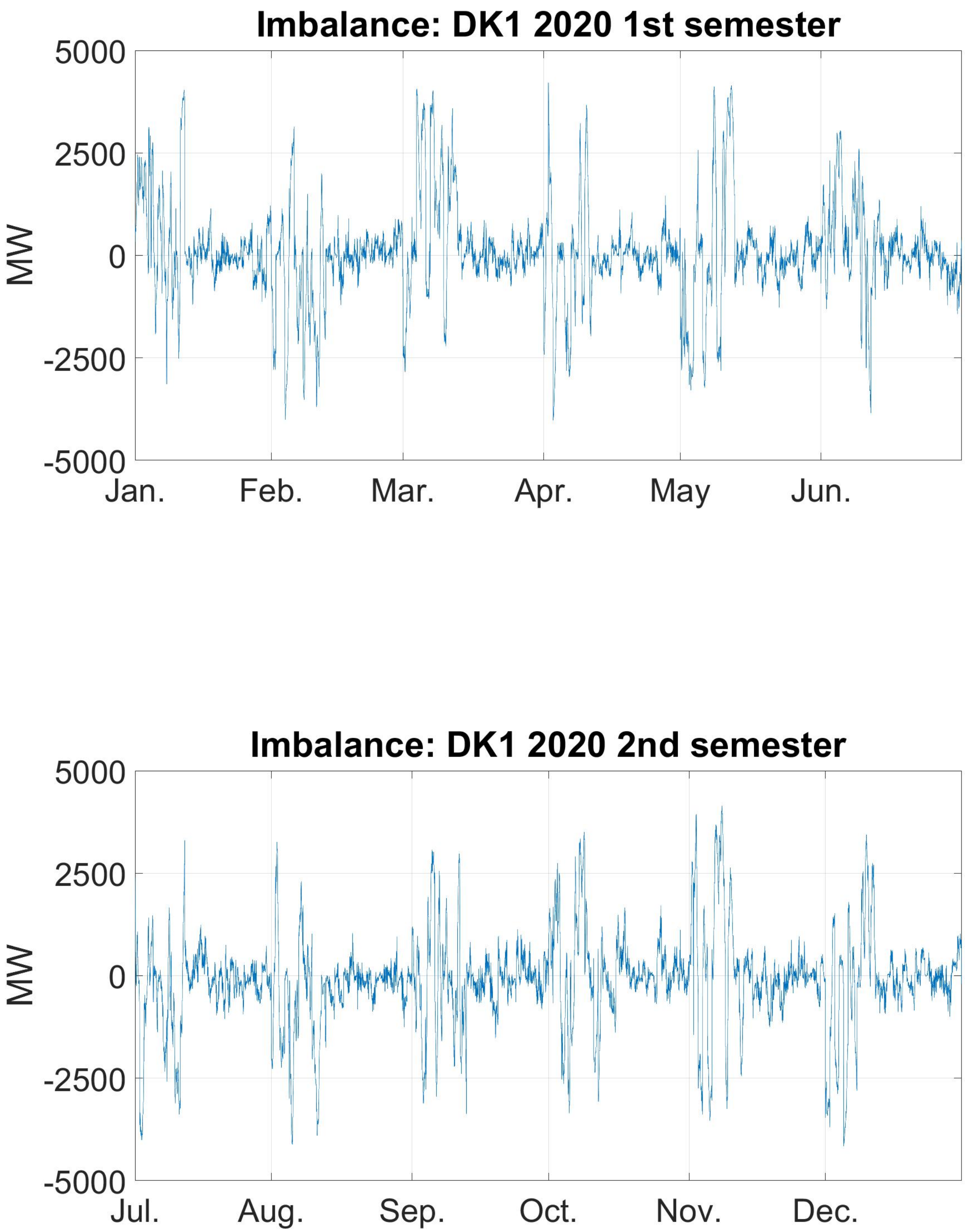


Fig. 9: The imbalance before balancing time series for DK1 region in the year 2020.

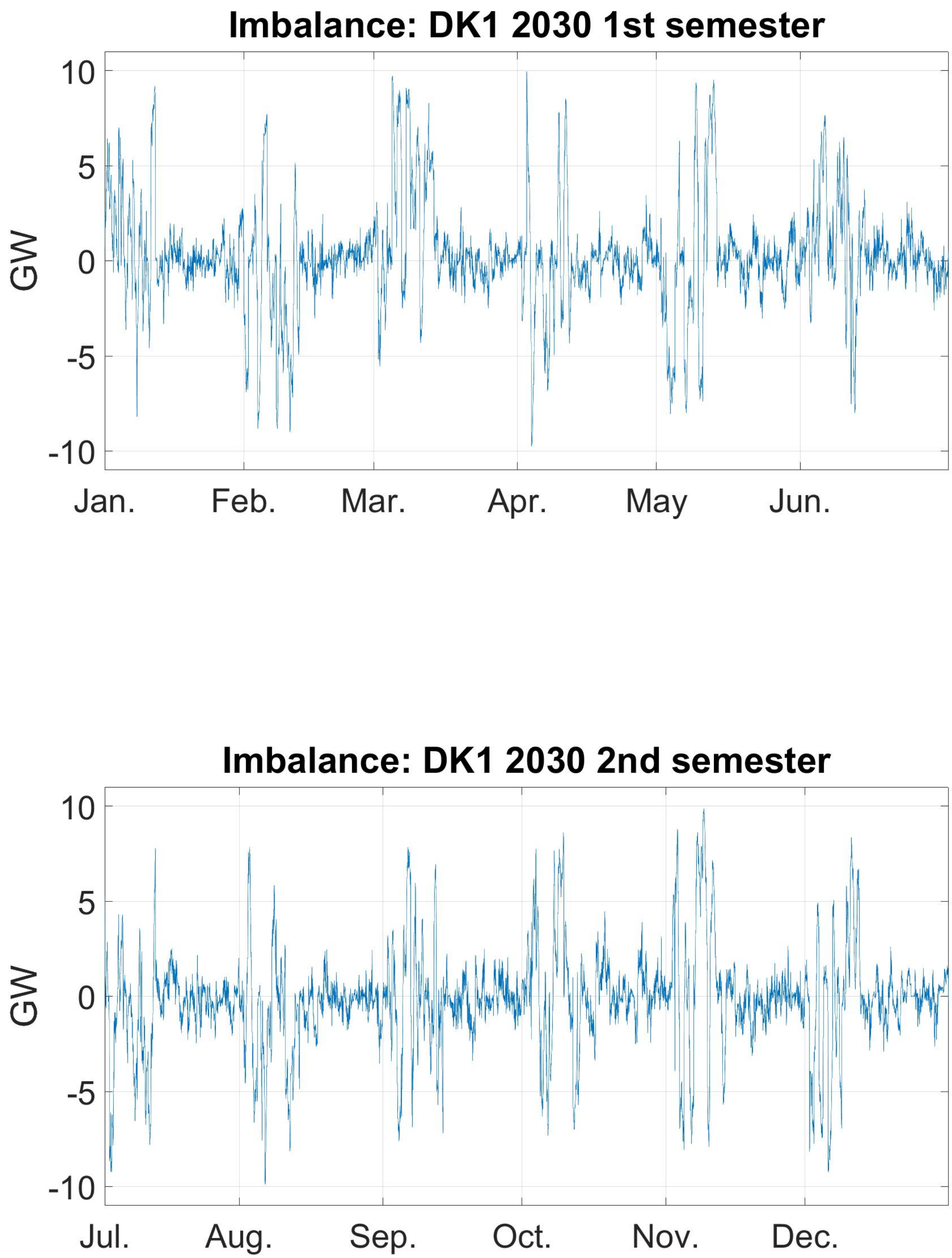


Fig. 10: The imbalance before balancing time series for DK1 region in the year 2030.

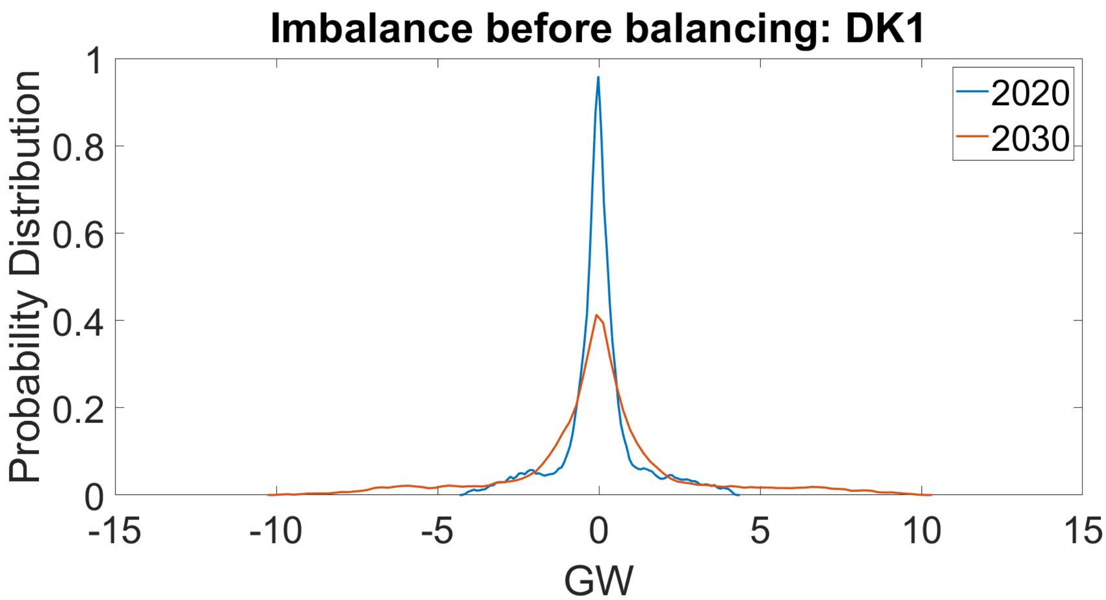


Fig. 11: Probability distribution of the simulated imbalances in the DK1 region in 2020 and 2030.

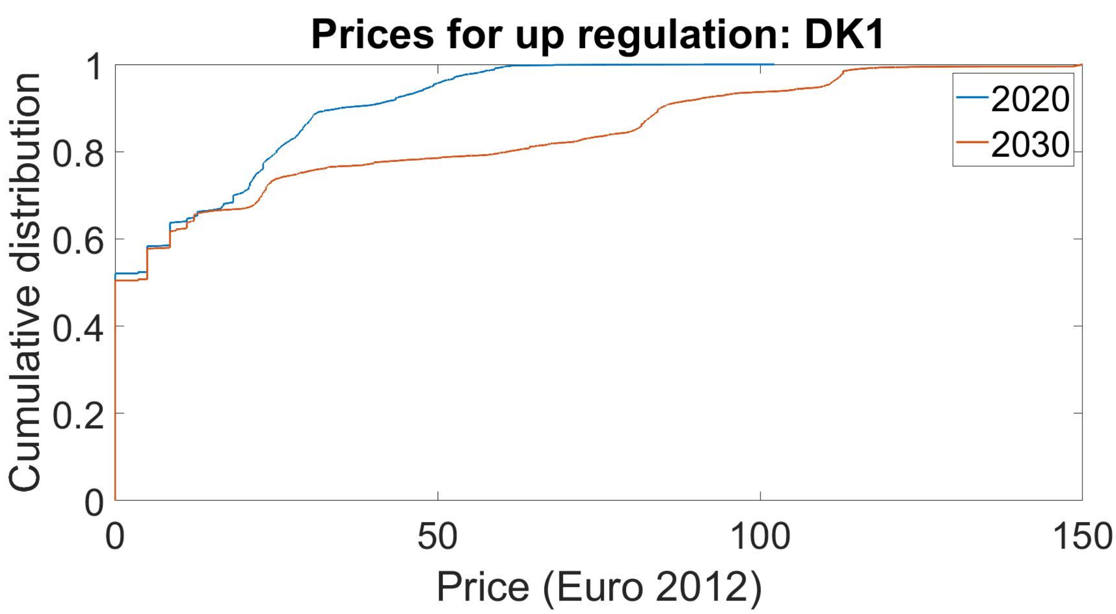


Fig. 12: Cumulative distribution of the simulated hour-ahead market price for up-regulation in DK1 region in the years 2020 and 2030. Prices are in Euros (2012 value since the considered meteorological data is from 2012).

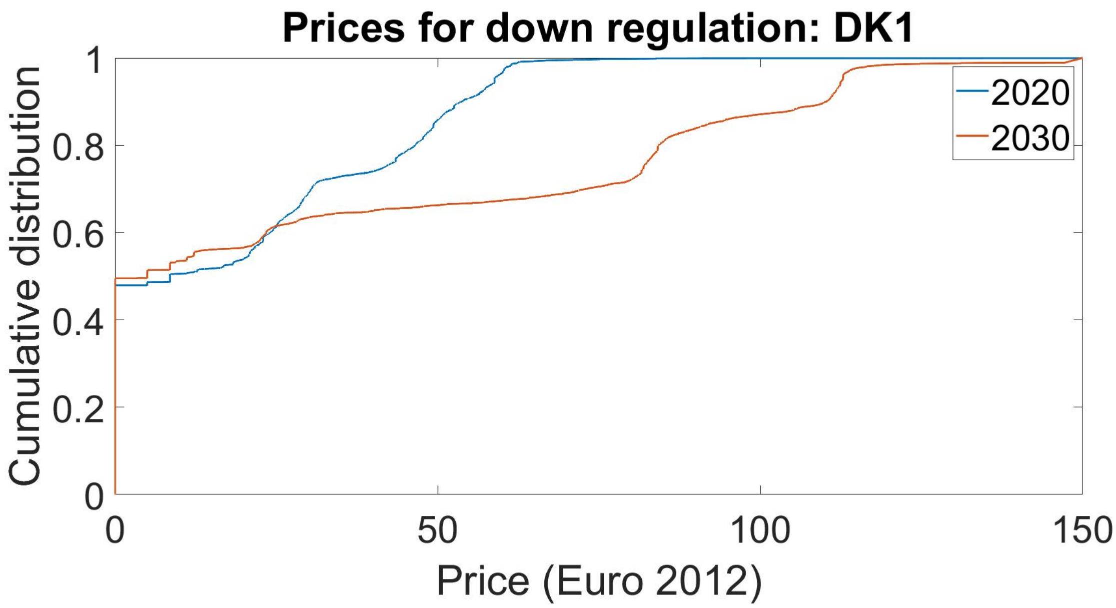


Fig. 13: Cumulative distribution of the simulated hour-ahead market price for down-regulation in DK1 region in the years 2020 and 2030. Prices are in Euros (2012 value since the considered meteorological data is from 2012).

3. Simulated wind speed and direction, correlated with the price time series

- **Down-regulation**
    1. Estimation of down-regulation prices
    2. Potential amount/volume of down-regulation in MW
    3. Simulated wind speed and direction, correlated with the price time series

1.5 Market Showcases

The showcases are built around the simulated *Scenarios* by considering perfect short-term forecasts, sensor measurements, etc. Three showcase sets are differentiated as:

1. High electricity prices
2. Low electricity prices
3. TSO-driven

The showcases are constructed around the assumption that the increasing share of wind power and flexible electricity prices will provide more pronounced incentives to include additional objectives in WFC than today. For example, electricity prices below the production costs provide a strong incentive to curtail the operation and consider rather other objectives such as the alleviation of structural loads or noise reduction.

Showcases for high and low prices are constructed by binning of the simulated price data. This is to quantify statistical overview of the potential revenue increase via WFFC per wind speed and direction sectors. The region of interest for wind speed is 6 - 12m/s, and the data is classified within $\pm 1\, m/s$ bins. The wind direction sectors are divided into $\pm 15°$ for both the low and high price scenarios.

For the FarmConners showcases, only the DA prices are included. Especially in the long term, *i.e.* for 2030 scenarios, it might be increasingly relevant to include balancing prices as they are expected to increase further and have a bigger share in the revenue generation for wind power plants. Accordingly, the balancing price time series are included in the data package that is released as a part of the FarmConners showcases, although not included in the market showcases themselves for simplicity. The prices included in the showcases are grouped according to the quartiles in the respective distributions. The high electricity prices include the top quartile, *i.e.* the highest 25% of the 2020 and 2030 scenarios, whereas the low electricity prices include the second lowest bin to avoid zero prices enabling to report a positive income (and potentially gain as a performance indicator) as a part of the showcases.

1.5.1 High Electricity Prices

For the simulated day-ahead (DA) prices in *Simulation of day-ahead markets using OptiSpot*, the highest 25% of the 2020 and 2030 DA prices are collected. The corresponding weather data is included in the data package to be distributed.

2020 High Prices

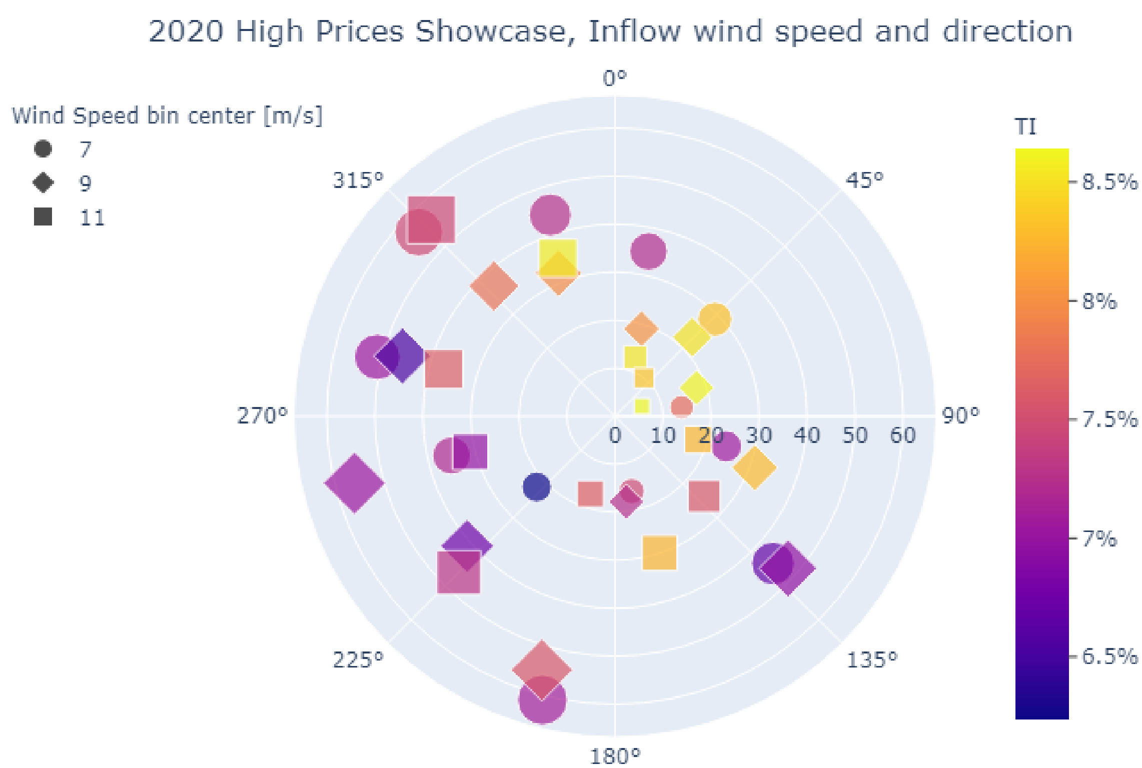


Fig. 14: 2020 High Prices Showcase overview of the meteorological data. The symbols show the wind speed bins ($\pm 1\ m/s$) in the region of interest for WFFC. The colour indicates the ambient turbulent intensity (TI) levels per wind direction sector ($\pm 15°$). The *frequency* on the x-axis refers to the number of hourly samples available for particular inflow case within the market showcase.

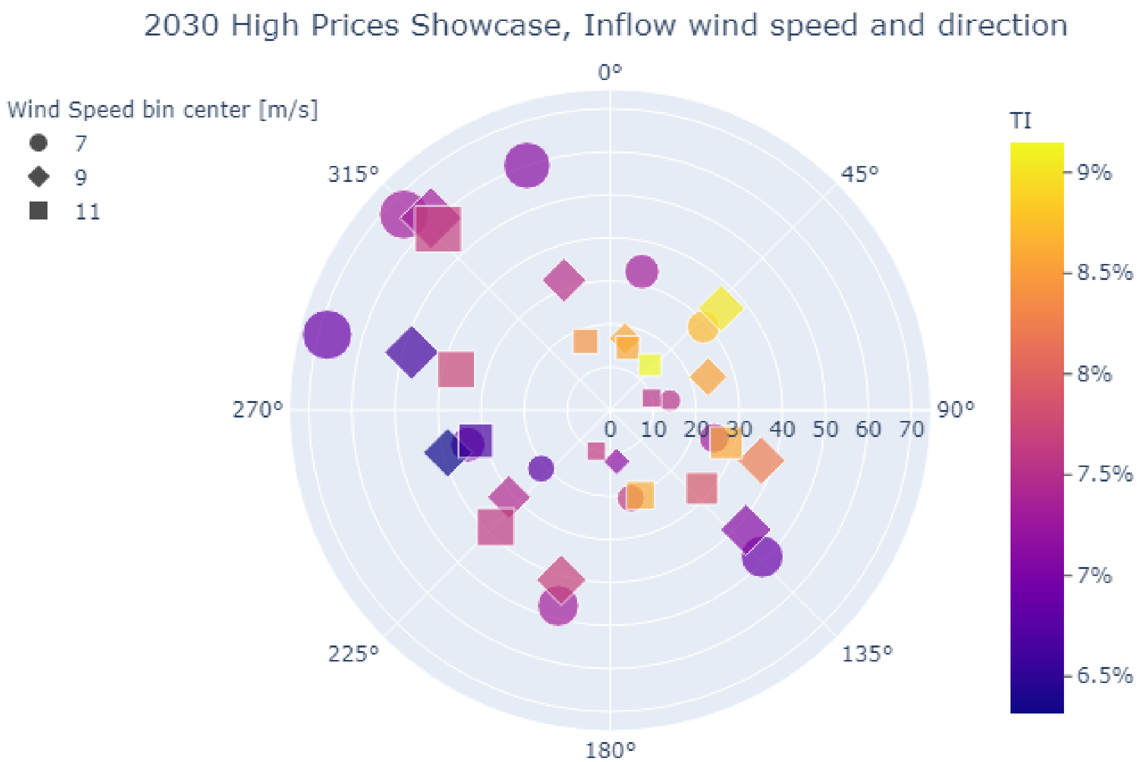


Fig. 15: 2030 High Prices Showcase overview of the meteorological data. The symbols show the wind speed bins ($\pm 1\ m/s$) in the region of interest for WFFC. The colour indicates the ambient turbulent intensity (TI) levels per wind direction sector ($\pm 15°$). The *frequency* on the x-axis refers to the number of hourly samples available for particular inflow case within the market showcase.

2030 High Prices

1.5.2 Low Electricity Prices

For the simulated day-ahead (DA) prices in *Simulation of day-ahead markets using OptiSpot*, the lowest 25% to 50% of the 2020 and 2030 DA prices are collected. Note that the lowest 25% quartile is avoided for the final showcase as it includes many zero-prices region in which the revenue maximization would be non-trivial. The FarmConners consortium suggests inclusion of storage and hybrid power plants for realistic and feasible low price revenue management - which is not included in this version of the Market showcases. The corresponding weather data is included in the data package to be distributed.

2020 Low Prices

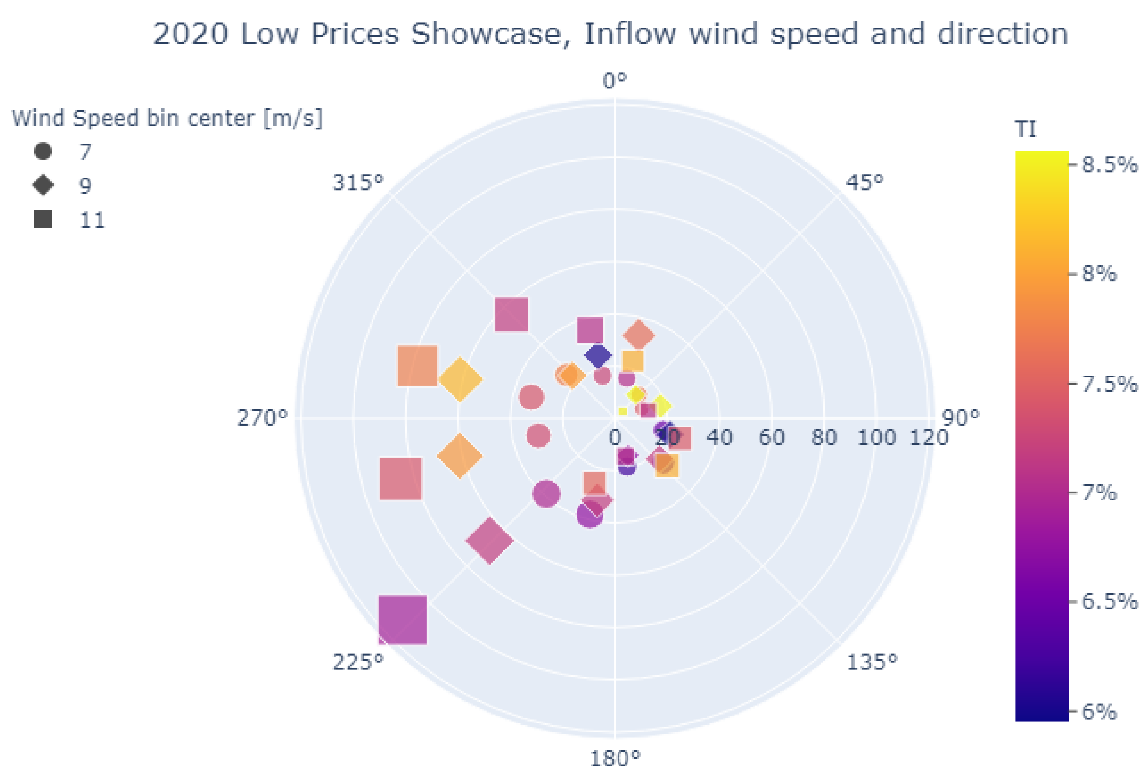


Fig. 16: 2020 Low Prices Showcase overview of the meteorological data. The symbols show the wind speed bins ($\pm 1\, m/s$) in the region of interest for WFFC. The colour indicates the ambient turbulent intensity (TI) levels per wind direction sector ($\pm 15°$). The *frequency* on the x-axis refers to the number of hourly samples available for particular inflow case within the market showcase.

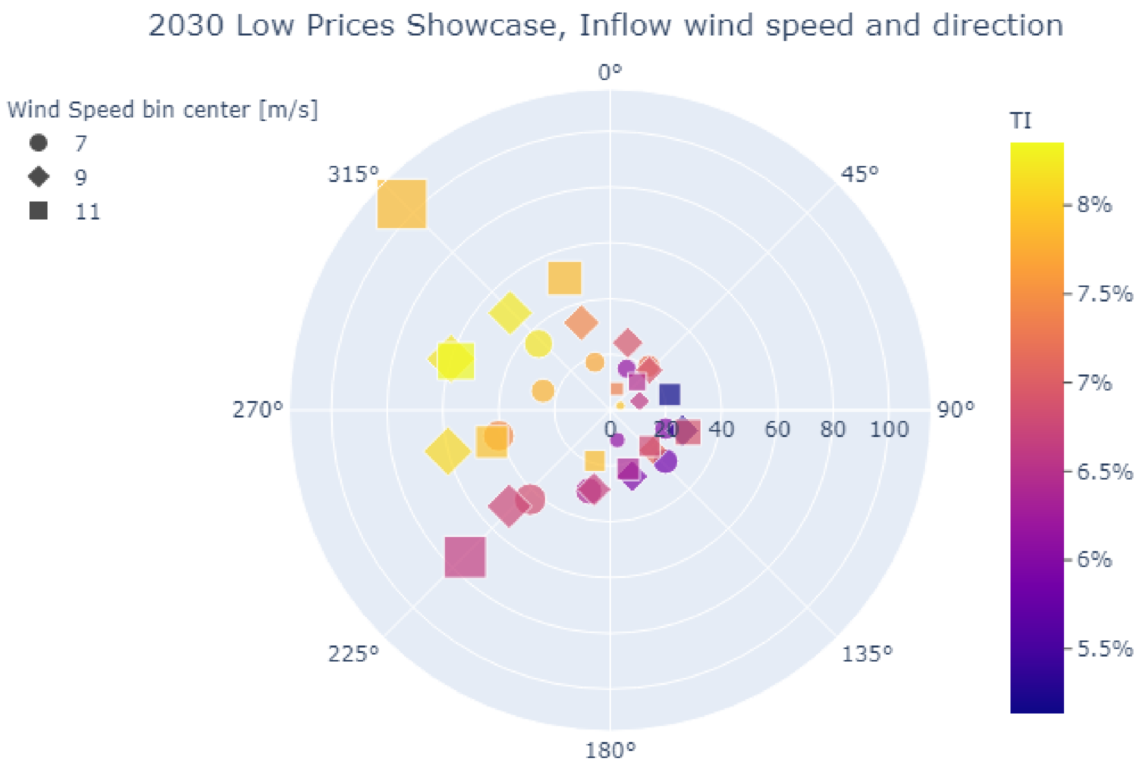


Fig. 17: 2030 Low Prices Showcase overview of the meteorological data. The symbols show the wind speed bins ($\pm 1\ m/s$) in the region of interest for WFFC. The colour indicates the ambient turbulent intensity (TI) levels per wind direction sector ($\pm 15°$). The *frequency* on the x-axis refers to the number of hourly samples available for particular inflow case within the market showcase.

2030 Low Prices

1.5.3 TSO-driven

In TSO-driven operation, an external signal is sent by the system operators (TSO/DSO) to reduce the active power output and operate in either balance-control or delta-control modes. Generally, balance control is used when the hosting capacity of the grid is reduced, while delta control is generally activated when WFs are down-regulated to provide power reserves. Possible causes for TSO-driven curtailment include:

1. Congestion in the system
2. System disturbance, *e.g.* faults in the grid

Compensation for the loss of production is either not provided or based on the agreement with the TSO, and thus, no time series for prices are required for that. The weather time series have however, been provided.

TSO-driven FarmConners market showcase requires **Maximum 75% of the rated capacity of the reference wind farm TC-RWP** (see *Reference Wind Farm*) for the given hourly weather time series for July and August as inflow as seen in *Simulation of aggregate and plant-level VRE in CorRES*.

1.6 Performance Indicators

Operating the WF with WFFC is compared to nominal operation without WFFC. The nominal operation serves here as baseline to evaluate the benefit of WFFC in the showcases.

1.6.1 Per Showcase

Here is the summary of the performance indicators per *Market Showcases* defined:

Showcase set	Performance Indicators
High Prices	income gain
Low Prices	income gain & alleviation of structural load as restriction (*i.e.* either load neutral or decrease in load components while increase in revenue)
TSO-driven	alleviation of structural load as restriction & index tracking of reference from TSO (*i.e.* decrease in load components compared to normal operation) (*i.e.* 75% of the rated TC-RWP power)

For high prices, it is assumed that maximum power production will be favoured to generate the highest possible income. There, the maximisation of the revenue is prioritised so there is no restrictions on the loads specified.

Low prices provide incentives to additionally perform structural load alleviation. Target levels for load alleviation are introduced as restrictions for the low-price showcases. The income gain is again used as a measure to compare operational strategies that fulfil a particular load alleviation to be reported as an outcome of the market showcase participation.

In the TSO-driven case, the produced power is set by the operator command, and thus, the income is determined, *i.e.* no changes attributed to income gain/power production. Therefore, the measures for comparison will be the level of structural load alleviation with respect to the baseline and the extent to which the reference from the TSO is followed, since its non-compliance may lead to penalties.

The restriction of structural loads in the low prices and TSO-driven scenarios are based on the loads if the WF is operated without WFFC, *i.e.* loads should either be equal or lower than in nominal operation. It will depend on the models and tools used by the showcase participants which components can be considered.

1.6.2 Evaluation indices

- The **income** metric is defined as the relative income gain achieved with respect to the nominal case without WFFC (*i.e.* normal operation).

$\text{income gain} = \text{price [per MWh]} \cdot \Delta P \cdot \texttt{bin}_h ours \texttt{bin}_h ours_{\texttt{bin}_h ours_{\texttt{bin}_h ours}}$ `with`