

Winds of the North Sea in 2050 - Public Final Report

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SAMENVATTING

Whiffle, TU Delft en KNMI hebben gezamenlijk het project 'Winds of the North Sea in 2050' (WINS50) uitgevoerd. Het project is uitgevoerd in het kader van TKI Wind op Zee en gesubsidieerd door het Ministerie van Economische Zaken. Het project startte op 1 januari 2020 en eindigde op 31 december 2023. Dit rapport beschrijft de belangrijkste activiteiten en resultaten van het project.

Het doel van WINS50 was het verminderen van onzekerheden over de interacties tussen een grootschalige uitrol van windenergie op de Noordzee en de atmosfeer. Daarom zijn simulaties uitgevoerd met atmosferische modellen voor zowel een hedendaags als een (hypothetisch) toekomstig capaciteitsscenario, representatief voor het jaar 2050. Een grote hoeveelheid modeluitvoer is publiekelijk beschikbaar gemaakt. Deze gegevens stellen onderzoekers uit de meteorologische en energie gemeenschappen, maar ook beleidsmakers, in staat gedetailleerde analyses te maken van bijvoorbeeld toekomstige windparkzogeffecten en energieproductie.

Modelsimulaties zijn uitgevoerd met het HARMONIE-AROME weermodel van KNMI. Daarnaast is een nieuwe versie van Whiffle's large-eddy simulatiemodel ASPIRE ontwikkeld dat geschikt is voor het uitvoeren van simulaties op de schaal van de gehele Noordzee. Met dit nieuw ontwikkelde model is een hedendaags en een toekomstig capaciteitsscenario met ongekend detail gesimuleerd.

Naast het leveren van datasets op het gebied van meteorologie en energieproductie, bestudeerde het WINS50 project de impact van een grootschalige uitrol van windenergie op de Noordzee op de atmosfeer. De simulatieresultaten geven aan dat in een 2050 scenario grote delen van de Noordzee beïnvloed worden door zogeffecten van windparken. De toegenomen verticale menging als gevolg van de vele windparken heeft ook invloed op de temperatuur- en vochtigheidsprofielen. Tegelijkertijd zal in een scenario voor 2050 de impact op de windsnelheid boven land klein zijn. Als gevolg van de toegenomen dichtheid van windparken op zee zal de efficiëntie van toekomstige windparken lager zijn dan die van de huidige windparken.

Gevoeligheidsstudies geven aan dat de productie aanzienlijk toeneemt als het nominale vermogen van de individuele turbines groter wordt bij een gelijkblijvend totaal geïnstalleerd vermogen (bijvoorbeeld n maal 20 MW turbines versus $2n$ maal 10 MW turbines). Zelfs voor turbinetypen met een vergelijkbaar nominaal vermogen maar enigszins verschillende vermogenscurven werden significante verschillen in productie gevonden. Een gevoeligheidsstudie met vrijwel oneindige windparken geeft inzicht in de limieten van windenergieproductie op zee.

ABSTRACT

Whiffle, TU Delft, and KNMI have jointly executed the 'Winds of the North Sea in 2050' (WINS50) project. The project was done in the framework of TKI Wind op Zee and subsidised by the Dutch Ministry of Economic Affairs. The project started at 1 January 2020 and ended 31 December 2023. This report describes the main activities and results from the project.

The aim of WINS50 was to reduce uncertainty about the interactions between large-scale offshore wind in the North Sea and the atmosphere. Therefore, simulations have been performed with atmospheric models for both a present-day and a (hypothetical) 2050 capacity scenario. A large volume of model output has been made publicly available. These data enable researchers from the meteorological and energy communities, as well as policy makers, to make detailed analysis of, for instance, future wind farm wake effects and energy production.

Model simulations were done with the HARMONIE-AROME model from KNMI. In addition, a new version of Whiffle's large-eddy simulation model ASPIRE was developed that is suitable for performing simulations at the scale of the entire North Sea. With this newly developed model, a present-day and a future capacity scenario have been simulated with unprecedented detail.

Besides providing meteorological and power production datasets, the WINS50 project studied the impact of a large-scale rollout of offshore wind energy in the North Sea. The simulation results indicate that in a 2050 scenario, large areas of the North Sea will be affected by wind farm wake effects. Increased vertical mixing from wind farms affect also temperature and humidity profiles. At the same time, in a 2050 scenario the impact on the wind speed over land will be insignificant. As a result of the increased density of offshore wind farms, the efficiency of future wind farms will be lower than for present-day wind farms.

Sensitivity studies indicate that production numbers increase significantly when the rated power of the individual turbines is larger while keeping the total installed capacity the same (eg n times 20 MW turbines versus $2n$ times 10 MW turbines). Even for turbine types with similar rated power but slightly different power curves, significant differences in production were found. A sensitivity study with virtually infinite wind farms provides insights in the limits of the offshore wind energy production.

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1 Introduction

As part of the energy transition, the installed capacity of offshore wind energy in the Dutch part of the North Sea will grow explosively in the next decades. Scenarios with up to 72 GW of offshore wind in 2050 are being examined by various research institutes and by the Dutch government (e.g. [Matthijssen et al., 2020], [Cleijne et al., 2020], [Rijksoverheid, 2021], [Rijksoverheid, 2024]). To date, it is highly uncertain how such a large-scale roll-out of wind energy will impact on the atmosphere and vice versa. A better understanding of these interactions is vital for the wind energy sector and policy makers.

The WINS50 project aimed to reduce uncertainties between a large-scale rollout of offshore wind energy in the North Sea and the atmosphere.

In particular, the objectives of the project were (1) to supply the wind energy sector and policy makers with the most up-to-date wind atlas that incorporates existing and future wind farms, (2) to develop a high-resolution (100 m) weather model covering the entire Dutch North Sea that can be used for operational forecasting and wind resource assessments, (3) to increase the understanding of the possible future wind climate of the North Sea, and (4) to provide detailed timeseries of power production for energy studies. Data and results of the WINS50 project facilitate additional integration studies such as for energy storage needs, electricity network planning and ecological studies.

1.1 Activities

To achieve the project goals the following activities have been performed.

- A three-year (2019-2021) simulation with HARMONIE-AROME, the operational weather model of KNMI (Work Package 1, Section 2). No wind farms are included in this simulation. It can be considered an extension of the Dutch Offshore Wind Atlas (DOWA) project [Wagenaar, 2020] and serves as an undisturbed reference ('control') simulation in the WINS50 project.
- The development of a Large-Eddy Simulation (LES) based weather model, suitable for performing simulations of the entire North Sea at a grid spacing of 100 m (Work Package 2, Section 3).
- HARMONIE-AROME wind farm simulations (Work Package 3, Section 4). This involves a three-year (2019-2021) simulation with the actual operational installed wind farms and a one year simulation with a hypothetical 2050 energy capacity scenario.
- Production of an LES North Sea wind climatology with Whiffle's LES model ASPIRE for both a present-day and a future 2050 energy capacity scenario (Work Package 4, Section 5).
- Validation and analysis of the future capacity scenario (Work Package 5, Section 6). This involves analyses of the impact of a large-scale rollout of the offshore energy capacity on the atmosphere and the associated power production.
- Sensitivity studies (Work Package 6, Section 7). By means of separate modeling studies the impact of applied turbine type, installed capacity density, and the limits to offshore energy production are discussed.

Each of the following Sections of this report describes actions and results for one of the project's Work Packages as listed above.

1.2 Results

The WINS50 project delivered three types of results:

- Improvements in the weather models used by Whiffle and KNMI.
- Datasets of both meteorological parameters and energy production for the model simulations listed in Sect. 1.1.
- Reports that study the impact of a future North Sea energy capacity scenario (e.g. the present report).

2 Work package 1 — HARMONIE undisturbed 2019-2021

2.1 Introduction

The WINS50 project can be considered the natural successor of the Dutch Offshore Wind Atlas (DOWA) project [Wagenaar, 2020]. In this project, a long-term wind climatology of the North Sea was made with the HARMONIE-AROME weather model covering the period of 2008-2018. In the framework of the WINS50 project, the DOWA wind atlas has been extended by three more years (2019-2021). In this simulation no effects of wind farms are included. As such, in the WINS50 project it serves as an undisturbed reference (or control) simulation.

To put the years 2019 to 2021, that have been simulated in WINS50 project, into a long-term perspective, Fig. 1 shows the annual mean 100 m wind speed obtained from ECMWF's global re-analysis dataset ERA5 ([Hersbach et al., 2020]) for a location in the southern North Sea. Data for the period 2004 to 2021 are included. Also, frequency distributions for individual years are shown with colors highlighting the years 2019, 2020, and 2021. It appears that the mean wind speed in 2019 was close to the long-term value, that 2020 was one of the windiest years, and that wind speeds in 2021 were lower than average.

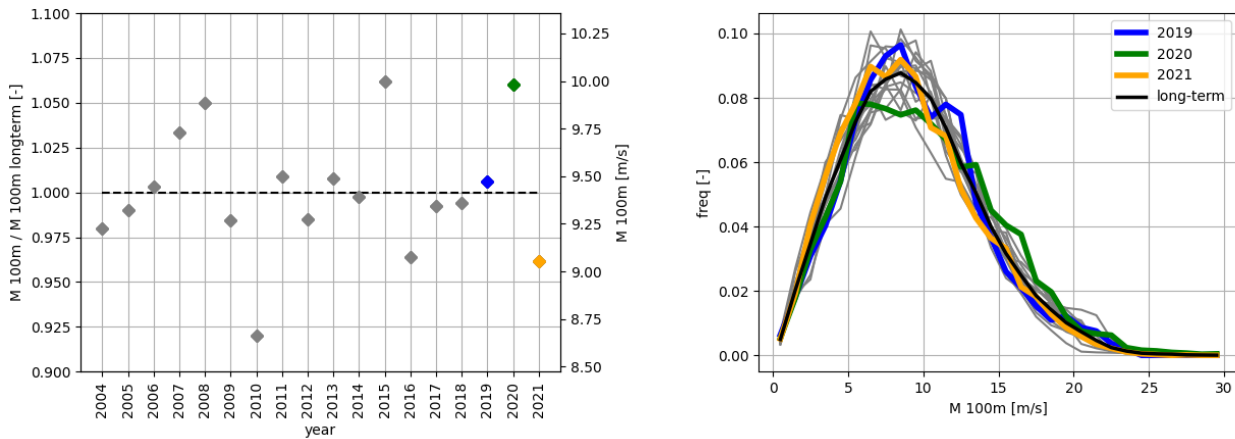


Figure 1. ERA5 100 m wind speeds over the North Sea for 2004 - 2021. Left: mean annual values. Right: yearly frequency distributions.

2.2 Model setup

HARMONIE-AROME (HIRLAM ALADIN Research On Mesoscale Operational NWP in Europe) is the operational Numerical Weather Prediction model of KNMI since 2012. It is a limited-area model, that was developed by a consortium involving many European countries. HARMONIE-AROME is a non-hydrostatic model, meaning that instead of employing the hydrostatic approximation, which often breaks down in severe-weather events, the vertical momentum equation is solved explicitly. More details on HARMONIE-AROME are given in [Bengtsson et al., 2017].

The simulation domain of the HARMONIE-AROME WINS50 simulations is similar to the domain used in DOWA. It consists of 789 by 789 grid points (grid spacing of 2.5 km) and is centered around Cabauw (Fig. 2). Lateral boundary conditions are taken from ERA5. Satellite and aircraft measurements were assimilated using a 3DVAR assimilation model.

In order to create a homogeneous dataset, changes in method should be avoided, but it turned out that HARMONIE-AROME Cycle 40 that was used for DOWA could no longer be used for WINS50. Instead, for WINS50 an updated version of HARMONIE-AROME was used: Cycle 43. Differences between the two model versions and the consequences for the continuity between the DOWA and WINS50 datasets were discussed in [Theeuwes et al., 2021]. It was concluded the impact on the 100-m offshore wind speed is less than the typically required measurement accuracy of 2%.

A validation of the three-year undisturbed HARMONIE-AROME simulation for WINS50 is presented in Section 6.

2.3 Data availability

For part of the simulation domain a dedicated set of output files was created. This subdomain (217x234 grid cells) is similar to the DOWA subdomain. It is indicated by the red rectangle in Fig. 2.

All HARMONIE-AROME data files can be downloaded from the KNMI Data Platform via <https://dataplatform.knmi.nl/>. The most convenient way to download files is via an API. More details, including an example download script, can be found at the WINS50 website under the Data Section (www.wins50.nl/data).

Data are available as NetCDF files. Two different formats are available:

- WINS50 - Daily 3d files (i.e. spatial representation): this dataset consists of daily NetCDF files for the DOWA/WINS50 subdomain. Each daily file contains hourly data (from 00 UTC up and including 23 UTC) for five parameters (temperature, wind speed and direction, pressure and relative humidity) at 17 height levels (10, 20, 40, 60, 80, 100, 120, 140, 150, 160, 180, 200, 220, 250, 300, 500 and 600 m). The size of one daily file is around 245 MB.
- WINS50 - Time series files, covering the three simulated years for individual 2,5 km grid points. Each time series file contains time series of all available parameters (5) at all available levels (17) for a particular location. The time series files contain exactly the same data as the daily 3D files. They are just organized differently to suit different users.

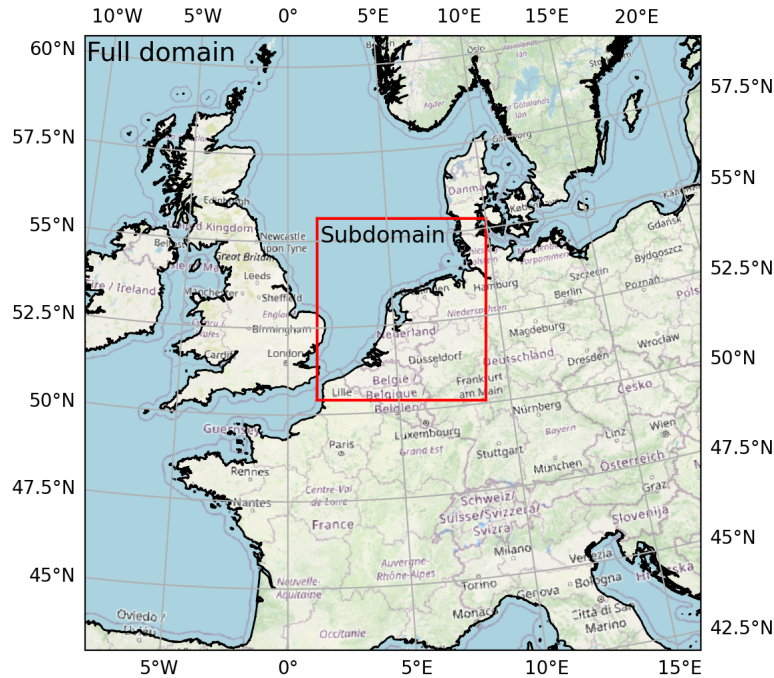


Figure 2. HARMONIE-AROME simulation domain. The red box indicates the area for which data has been made publicly available.

3 Work package 2 — Developing an LES-based weather model

3.1 Introduction

This Section describes the model developments that were required in order to perform LES on a domain covering the entire Southern North Sea. In addition, a basic model description is included.

3.2 Background

Operational Numerical Weather Prediction (NWP) models are based on the Reynolds-Averaged Navier-Stokes (RANS) equations. They only compute flow averages and rely on additional models to account for the effects of turbulence. They usually operate at grid spacings of 1 to 10 kilometers. On the other hand, Direct Numerical Simulation (DNS) of the Navier-Stokes equations is possible, but this requires such a wide range of length and time scales that it is considered computationally infeasible for realistic weather simulations.

The premise of LES is that computational costs can be reduced by modeling the smallest length scales (the computationally most expensive to resolve) by low-pass filtering of the Navier-Stokes equations (using a so-called subgrid-scale model). At the same time, in LES the largest, most energetic turbulence fluctuations are still being resolved. In this way the LES technique combines the practical relevance of RANS modeling with the high-fidelity of a turbulence resolving model. The typical grid spacing of LES simulations ranges from 10 to 100 *m*.

For WINS50, simulations with Whiffle's LES model ASPIRE (Atmospheric Simulation Platform for Innovation, Research, and Education) have been made. The origin of ASPIRE lies in an LES code that is commonly referred to as DALES: Dutch Atmospheric Large Eddy Simulation [Heus et al., 2010]. While LES is often considered the benchmark methodology in atmospheric flow and wind farm wake modelling it is often considered too expensive for operational use, see e.g. [Beaucage et al., 2014]. To overcome the computational barrier of LES modelling, ASPIRE performs the majority of its computational routines on Graphics processing units (GPUs), which makes it fast enough for operational forecasting on practically relevant simulation domains ([Schalkwijk et al., 2015a]).

3.3 Model developments

In WINS50, Whiffle's LES model ASPIRE is used to perform LES simulations at a domain of roughly 300 by 500 km. In order to enable sensible simulations at a domain of this size, major model development steps had been carried out.

The most fundamental development concerns the transition from a model with periodic boundary conditions to a model with open/prescribed boundary conditions. Most LES models apply periodic boundary conditions. Also within WINS50, ASPIRE has been used with periodic boundary conditions for research studies with limited domain sizes (see Section 7). For these studies the LES is driven by large-scale weather tendencies derived from the ERA5 re-analysis dataset. These dynamic tendencies are applied uniformly over the domain. It is equivalent to the way so-called single-column models from numerical weather prediction models are being driven (e.g. [Neggers et al., 2012], [Baas et al., 2017]). Although this way of large-scale meteorological coupling of LES models has been very successful (e.g. [Schalkwijk et al., 2015b], [Baas et al., 2023]) it cannot be applied for larger domains. For instance, it is impossible to have spatial gradients over the domain when using periodic boundary conditions. And, of course, the concept of periodicity becomes increasingly unrealistic with growing domain sizes.

In the prescribed boundary conditions setting, ASPIRE has a one-way nesting structure as applied in most limited-area NWP models. The model state of the outer domains is prescribed at the boundaries of the inner domains. In the inner domain of ASPIRE, which has a typical grid spacing of 10 to 100 *m*, the LES equations are solved. Case and time specific inflow turbulence is generated by means of a concurrent (periodic) LES simulation. Most frequently, ASPIRE is driven by data from ECMWF or ERA5, although in principle data from any NWP model could be utilized. In order to bridge the gap between the coarse ERA5 grid (around 30 *km*) and the fine LES grid of the inner domain, an additional simulation is applied with a grid spacing of typically 2 to 3 *km*. This so-called mesoscale simulation is nested directly in ERA5, while the boundary conditions of the smaller LES domain are extracted from the mesoscale simulation. For the mesoscale domain, the same model formulation is used as for the inner LES domain, apart from the turbulence, which is not resolved but completely parameterized.

The difference between periodic and prescribed BCs is illustrated in Figure 3.

The second model development carried out in the framework of the WINS50 project is the ability to do a simulation on multiple GPUs. This allows for larger computational domains as the available memory increases. For developing the multi-GPU capability, an efficient pressure solver and a fast interconnection between the GPUs turned out to be key.

3.4 Model description

3.4.1 Governing equations

The governing equations of ASPIRE are summarized in [Baas et al., 2023].

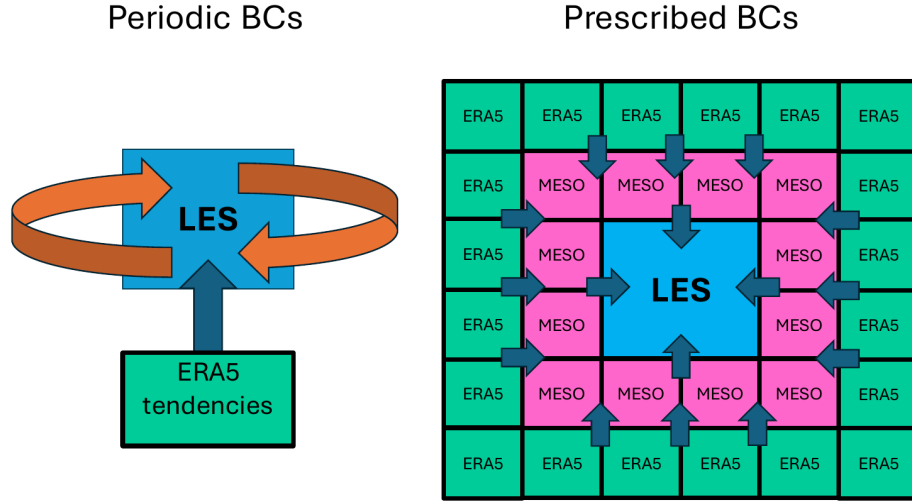


Figure 3. Schematic illustration of the difference between periodic boundary conditions (left) and prescribed boundary conditions (right).

3.4.2 Lower boundary conditions

As a lower-boundary condition, ASPIRE uses a modified version of the Tile ECMWF Scheme for Surface Exchanges over Land (TESSEL) model that has been developed by, and is used by, ECMWF ([ECMWF, 2017]). Over water surfaces a Charnock relation ([Charnock, 1955]) is applied with a Charnock constant of 0.0185.

3.4.3 Turbine modeling

In ASPIRE, wind turbines are modeled by a so-called actuator-disk model. Individual turbines are modeled as a semi-permeable disk that exerts forces on the flow that are consistent with the thrust curve of the wind turbine. In this way, wind farm wake effects are taken into account. In addition, using the turbine power curve, the turbine parameterization allows to directly model power output per turbine on a high temporal resolution. The actuator-disk model is implemented following [Meyers and Meneveau, 2010], [Calaf et al., 2010]. The drag force exerted on the flow by a wind turbine is modelled as

$$F = -\frac{1}{2}\rho AC'_t \overline{M_D}^2$$

where ρ is the air density, $A = \pi R^2$ is the frontal area of the rotor and C'_t the thrust coefficient based on the disk-averaged wind speed, $\overline{M_D}$. Wind turbine power is given by

$$P = \frac{1}{2}\rho AC'_p \overline{M_D}^3$$

with C'_p the disk-based power coefficient. The disk-based power and thrust coefficients are determined from the manufacturers power- and thrustcurves by means of an offline simulation. This additional step is required since the manufacturer curves are based on a free-stream wind speed, $\overline{M_\infty}$, a reference density, ρ_0 , and a reference turbulent intensity, TI_{ref} . An additional advantage of this approach is that the turbines by definition produce the correct power and thrust for the given grid configuration. The present implementation of the actuator-disk model has been tested extensively in operational practice and shows good performance for a wide range of numerical grid settings.

3.4.4 Input data sets

Specific site conditions are incorporated by utilizing publicly available datasets. For terrain elevation, the global ALOS Global Digital Surface Model ALOS World 3D - 30m (AW3D30) dataset is used with a horizontal resolution of 30 m ([ALOS, 2024]). For land use, ESA's WorldCover dataset is applied, which provides global information on land use on a 10 m resolution ([Zanaga et al., 2021]).

4 Work package 3 — HARMONIE wind farm simulations

4.1 Introduction

This Section describes the setup of the HARMONIE-AROME simulations that include wind farms. Simulations are performed for a present-day and a hypothetical 2050 energy capacity scenario. First, the parameterization of wind farms in HARMONIE-AROME is briefly discussed. Second, the present-day and future capacity scenarios are presented. Third, publicly available data are described. For more detailed information we refer to [Wijnant et al., 2022] and the Data Section of the WINS50 website (www.wins50.nl/data).

4.2 Modeling wind farms in HARMONIE

The Wind Farm Parameterization used in the HARMONIE-AROME WINS50 simulations is based on the work of [Blahak and Wetter-Jetzt, 2010], [Fitch et al., 2012], and [Van Stratum et al., 2022]. The parameterization introduces an elevated momentum sink on the mean horizontal flow, a source of electrical energy, and a source of turbulent kinetic energy (TKE).

The parameterization assumes that wind turbines are an order of magnitude smaller than the grid size. Therefore, the model accounts for the influence of the total number of turbines in one grid cell. The turbine rotor intersects several model levels and the effects are estimated for each level separately, in accordance with the area of the rotor that intersects that particular level.

Drag of the turbines is modelled as a force that is constant across the rotor area but depends on the wind speed. The dependence of drag on wind speed is described by the thrust coefficient (C_t). The power coefficient (C_p) describes the fraction of kinetic energy that is converted into electricity. C_t and C_p and their relation to the wind speed depend on the turbine type.

4.3 Capacity scenarios

In the framework of WINS50 the following wind farm simulations have been performed with HARMONIE-AROME:

- A three-year simulation (2019-2021) including operational wind farms.
- A one-year simulation with a hypothetical 2050 wind farm scenario (using the meteorology of 2020)

This subsection describes how the capacity scenarios have been set up. Information on the wind farms that are included in the present-day scenario simulation and the future 2050 scenario is provided in a shapefile, available at https://wins50.nl/downloads/wins50_windfarm_scenarios.zip.

4.3.1 Present-day scenario

The present-day scenarios include all wind turbines that were operational in Europe (onshore and offshore) on the 1st of January of each of the three simulated years. Details on operational offshore wind farms and turbine types are obtained from different sources. Most of the turbine locations are obtained from OpenStreetMap. For some wind farms no turbine locations were available at the time of the model simulation. For these wind farms, the boundaries were taken from a wind farm shapefile obtained from the European Marine Observation and Data Network ([EMODnet, 2024]). Subsequently, for the concerning wind farms the required number of turbines were evenly distributed within the wind farm boundaries using an iterative repulsion method (for more information see [Van Stratum et al., 2022]). Also, wind farms over land are included in the simulations with their location obtained from WindStats (Netherlands) and The Wind Power (rest of the domain).

Following [Van Stratum et al., 2022], wind turbine power and thrust curves were obtained from various sources, predominantly from windPRO input database. For a small number of turbine types no data were available. For those turbine types either reference data from literature was used or data from comparable turbines.

Figure 4 (left panel) shows the locations of the offshore wind farms that are included in the simulations.

4.3.2 Hypothetical 2050 scenario

This simulation of the 2020 weather includes a hypothetical wind farm scenario with an installed capacity that is anticipated for the year 2050. For instance, in the WINS50 2050 scenario the installed capacity in the Dutch part of the North Sea (EEZ) is 53 GW (presently 4 to 5 GW), while for the entire North Sea this number amounts to 190 GW (presently around 20 GW).

The motivation for WINS50 2050 hypothetical wind farm scenario is extensively described in [Wijnant et al., 2022]. Here, only a basic description of the scenario is given.

In short, the WINS50 2050 scenario consists of three layers:

1. Present (operational) wind farms. These are the operational wind farms taken from the WINS50 2020 scenario, added with publicly available data on wind farm and turbine locations up to April 2021. These wind farms are modeled as realistic as possible.

2. Planned wind farms. These are wind farms for which actual wind farm boundaries are already published. Roughly, this concerns wind farms that will become operational before 2030. As much as possible we use actually planned installed capacities. For the Dutch planned wind farms, we use wind farm site boundaries as provided by RVO Offshorewind as available in April 2021.
3. Future wind farms. These are hypothetical wind farms. For this we make use of the future wind farm scenario of the WoZEP (Wind op Zee Ecologisch Programma) ([Van Duren et al., 2021]). Among others, the WoZEP future wind scenario is constructed to meet the 2050 offshore wind energy targets of the countries around the North Sea as known in 2018, using a capacity density of $8 \text{ MW}/\text{km}^2$, and a maximum wind farm size of 400 km^2 . Further motivation for the WoZEP scenario can be found in [Zijl et al., 2021].

Figure 4 (right panel) shows the locations of the offshore wind farms that are included in the hypothetical 2050 capacity scenario.

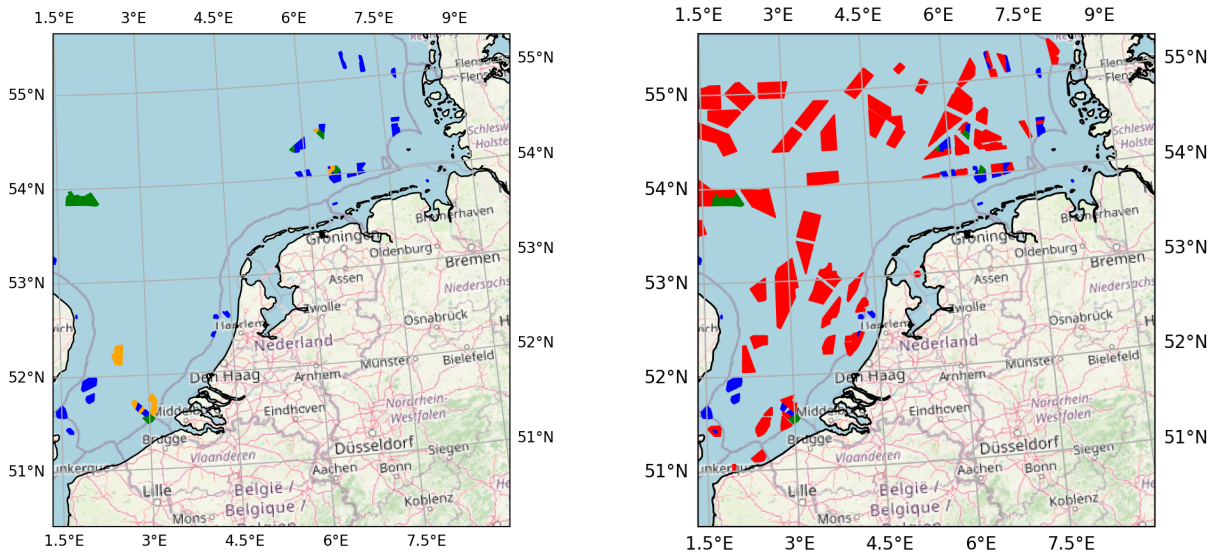


Figure 4. Wind farms in the present-day (left) and hypothetical 2050 (right) capacity scenarios (publicly available subdomain). For the present-day scenario, blue, green, and orange wind farms correspond to the 2019, 2020, and 2021 scenarios, respectively. The 2050 scenario also includes the 2019 (blue) and 2020 (green) wind farms. Planned and hypothetical future wind farms are indicated in red.

For the operational windfarms the applied turbine types are as realistic as possible (given information in April 2021). For wind farms that are expected to become operational in the coming years, we use the 10 MW DTU_10MW_178_RWT_v1 reference wind turbine. For wind farms that will be commissioned later (towards 2030) and for all hypothetical (future) wind farms we use the 15 MW IEA_15MW_240_RWT reference wind turbine. Characteristics of the reference turbines can be found at <https://nrel.github.io/turbine-models/Offshore.html>.

4.4 Data availability

As for the HARMONIE-AROME WINS50 simulation without wind farms, daily files with spatial meteorological data are available as well as time series files for individual grid points (see Sect. 2.3 for details). In addition, daily files with gridded power production data are provided, both for the simulation with the present-day scenario and the hypothetical 2050 scenario.

In an additional postprocessing step, the HARMONIE-AROME power data has been aggregated to timeseries for each individual wind farm. The production timeseries files can be downloaded via the WINS50 website (https://wins50.nl/downloads/wins50_harmonie_windfarm_powerproduction.zip)

5 Work package 4 — Production of the LES North Sea wind climatology

5.1 Introduction

Year-long LES simulations have been performed with the ASPIRE LES model for two energy capacity scenarios: one for the year 2020 including operational wind turbines and one with a hypothetical 2050 energy capacity scenario (using the 2020 meteorology). This Section describes the setup of the LES simulations and the publicly available output data.

5.2 Simulation set-up

The LES domain has a size of $327600 \times 491520 \times 6000 \text{ m}$, centered around 53.34N , 4.12E . A horizontal grid spacing of 128 m is applied. Figure 5 shows the spatial extent of the domain. For illustration, a 100 m wind field is added, showing significant wind farm wake effects. The lowest model level is 32 m thick. Above 340 m vertical grid stretching is applied. The domain contains $2560 \times 3840 \times 64$ grid cells. Prescribed boundary conditions are applied.

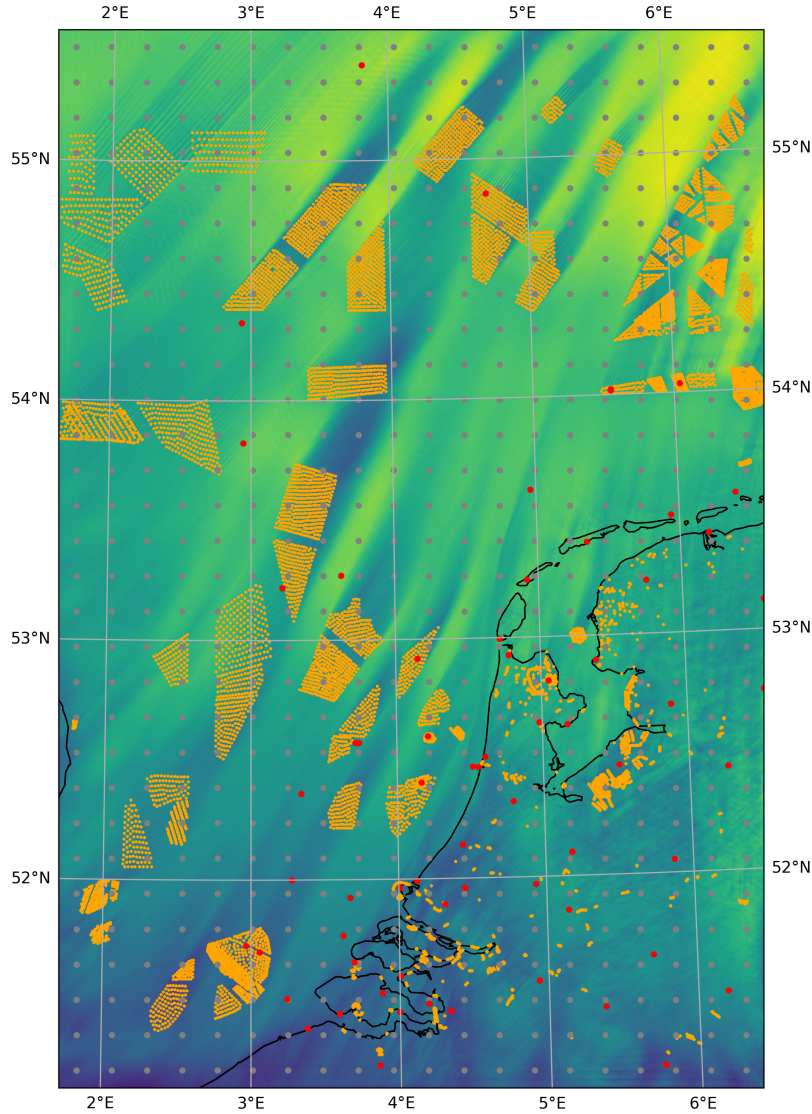


Figure 5. Computational domain of the ASPIRE simulations. Contours indicate an example 100-m wind field. Turbines are indicated with orange markers. Grey markers indicate a grid of 600 virtual metmasts for which model are available. The same is true for the red markers, but these correspond to observational locations.

To bridge the gap between the coarse ERA5 grid (around 30 km) and the fine LES grid (128 m) of the inner domain, an additional mesoscale simulation is applied. The mesoscale simulation (or ‘outer domain’) is nested directly in ERA5, while the boundary conditions of the LES domain are extracted from the mesoscale simulation. For the present study, the mesoscale domain has a size of 768 km and a grid spacing of 3 km . The height of the mesoscale domain is 10 km .

The ASPIRE simulations were done as separate daily simulations. For each day, the three-dimensional initial conditions were taken from the simulation of the previous day. As such, the year-long simulation can be considered as one continuous simulation.

The ASPIRE simulations were performed on a high-performance computing (HPC) cloud cluster hosted by Amazon Web Services. Four Pd4 instances with each eight NVIDIA A100 Tensor Core GPUs (40 GB) were used in parallel. To make optimal use of the four Pd4 instances, the two simulated years were divided into four half-year periods. For each half-year period one day of spin up was applied.

As an example, a one-day animation of modeled cloud and wind patterns (including wakes) can be viewed at <https://vimeo.com/manage/videos/907633072/6f4536bd5a>.

5.3 Energy capacity scenarios

Although small differences exist, the ASPIRE wind farm scenarios closely resemble the ones applied in the HARMONIE-AROME simulations described in Sect. 4.3. In the ASPIRE simulations, onshore turbines were taken from the map 'Windturbines - ashoogte', operated by RIVM (<https://www.atlasleefomgeving.nl/windturbines-december-2021-0>).

For the present-day scenario the LES domain contains 3470 turbines, corresponding to an installed capacity of 12.8 GW. For the hypothetical 2050 scenario the LES domain includes 10063 turbines representing an installed capacity of 100.7 GW. In Fig. 5 turbine locations for the 2050 scenario are indicated by orange markers.

5.4 Data availability

Data from the ASPIRE WINS50 simulations are publicly available via the Registry of Open Data on AWS at <https://registry.opendata.aws/whiffle-wins50/>. Data can be downloaded and/or plotted with simple python scripts. Example download scripts are provided online at the above-mentioned website.

Four different data sets are available:

- Horizontal fields

Two-dimensional cross sections of the entire simulated domain on hourly time resolution. Data are available at height of 10, 50, 100, 150, 200, 300, 400, 600, and 1000 m. Variables like wind speed, wind direction, temperature, humidity, but also surface fluxes are provided.

- Virtual metmasts on a regular grid

Spread over the domain, 600 virtual metmasts are located. In Fig. 5 these are indicated by grey markers. For these locations, profiles of mean variables and turbulent fluxes are available for all model levels (0 - 6000 m) on a 10-minute time resolution.

- Virtual metmasts at observation locations

Simulated meteorological quantities like wind speed, wind direction and turbulence intensity at 10-minute time resolution for around 60 locations corresponding to real-world measurement locations (RVO Lidars, KNMI Automatic weather stations) within the domain. Their locations are indicated by red markers in Fig. 5.

- Turbine data

Simulated time series of wind turbine-related variables (e.g. power production, wind speed, air density, etc.) for each individual wind turbine at a 5-minute time resolution.

6 Work package 5 — Validation and analysis of the 2050 capacity scenario simulations

6.1 Introduction

In the first part of this Section a basic validation of the HARMONIE-AROME and ASPIRE model simulations is presented. In the second part the impact of the large-scale deployment of offshore wind energy on both the wind climate and power production is analyzed.

6.2 Validation of the WINS50 simulations

6.2.1 HARMONIE-AROME

The Fitch wind farm parameterization within HARMONIE-AROME has been extensively validated in [Van Stratum et al., 2022]. They performed two one-year simulations, one including operational wind farms and a control simulation without wind farms. After comparison with available wind measurements, they concluded that the inclusion of the wind farm parameterization has a positive effect on the modeled wind fields: for all validation locations the absolute bias in wind speed was reduced compared to the simulation without wind farms. Furthermore, the predicted power production (compared to observed production of the Belgian offshore wind farms) was realistic.

Here, we compare modeled wind speed and direction of the HARMONIE-AROME simulations with available LiDAR and single-level observations (e.g. offshore platforms). The hourly HARMONIE-AROME output is compared to hourly-averaged observations. As an example, Figure 6 shows a basic plot of modeled versus observed wind speed and direction at 116 m height for the LiDAR operated at the K13 offshore platform. It includes three years of data from the undisturbed HARMONIE-AROME WINS50 simulation. For both wind speed and direction, the agreement between model and observations is excellent.

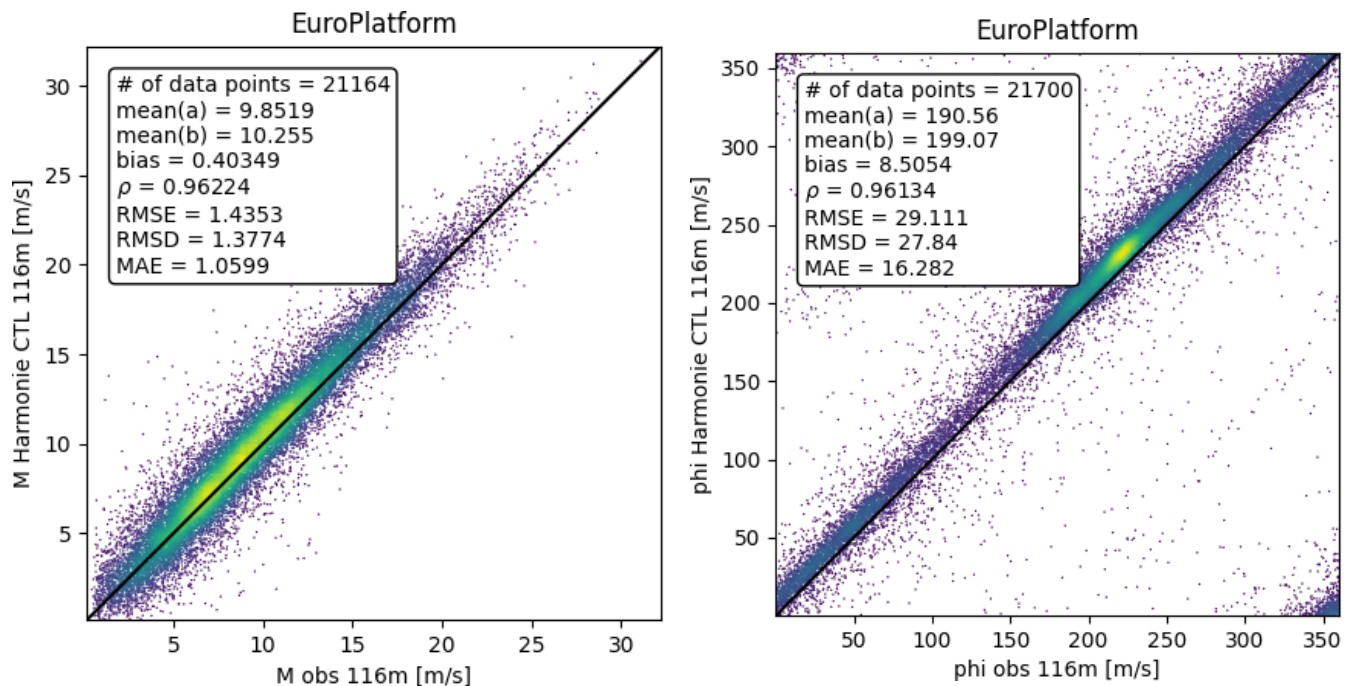


Figure 6. Scatterplot of modeled versus observed wind speed (left) and wind direction (right) at 116 m height for K13.

For a suite of offshore observational stations, Fig. 7 presents additional wind speed performance metrics, in particular the bias, the mean absolute error, the root mean square error and the Pearson correlation coefficient. For locations with multiple observation heights, the height closest to 100 m was selected. Numbers are based on a comparison of the full three year simulation period (2019 - 2021) for both the simulation with operational wind farms and the simulation without any wind farms. For location that are far from operational wind farms the difference between the undisturbed (CTL) simulation and the simulation including the wind farms (W20) is negligible. A difference between the two simulations at a location indicates that there is an impact of wake effects of nearby and/or more distant wind farms, at least as simulated by the model. Interestingly, when wake effects are present in the model this leads to a better correspondence with the observations. Performance metrics for locations at open sea are generally better than for stations that are located within a limited number of (2.5 km) grid points from the coast (e.g. Cadzand, Stavenisse, Hansweert).

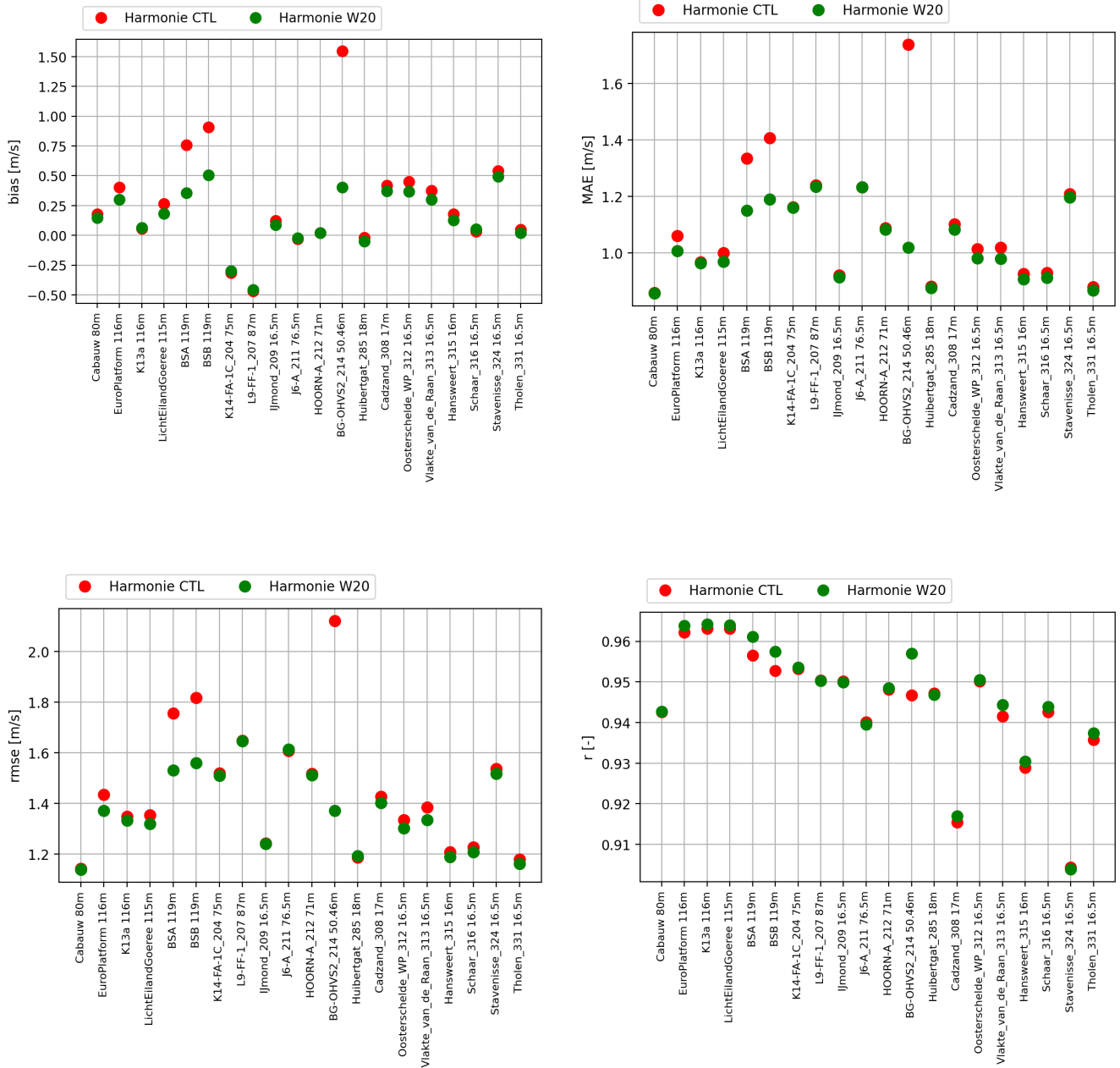


Figure 7. Wind speed performance metrics for offshore measurement locations. For each location, the evaluation height is indicated in the x-axis labels. Bias refers to the mean wind speed difference (model - observations), MAE to the mean-absolute error, rmse to the root-mean square error, and r to the Pearson correlation coefficient.

Most stations in Fig. 7 show a small positive bias. This corroborates the findings of [Dirksen et al., 2022] who performed a detailed evaluation of the HARMONIE-AROME WINS50 simulations with and without wind farms. Focusing on the year 2019, they conclude that including the wind farms in the simulation gives a better representation in wake-affected conditions. They confirm that wakes are strongest in stably-stratified conditions, which was also found in other/earlier studies (e.g. [Cañadillas et al., 2020], [Platis et al., 2022]). The impact of wind farm wakes is noticeable up to distances of at least 50 km.

Spatial characteristics of wind farm wakes have been studied by [Wijnant and Stepek, 2023], who compared model output of the HARMONIE-AROME WINS50 simulations with satellite-based Synthetic Aperture Radar (SAR) winds for the period 2019-2021. They conclude that near-surface wake effects are underestimated by the HARMONIE-AROME WINS50 simulations.

6.2.2 ASPIRE

Figure 8 presents scatterplots of modeled versus observed wind speed (around 100 m) for four locations spread over the North Sea based on 10-minute time intervals. The error metrics show good correspondence between model results and observations. In general, the wind speeds of the ASPIRE WINS50 simulations have a positive bias.

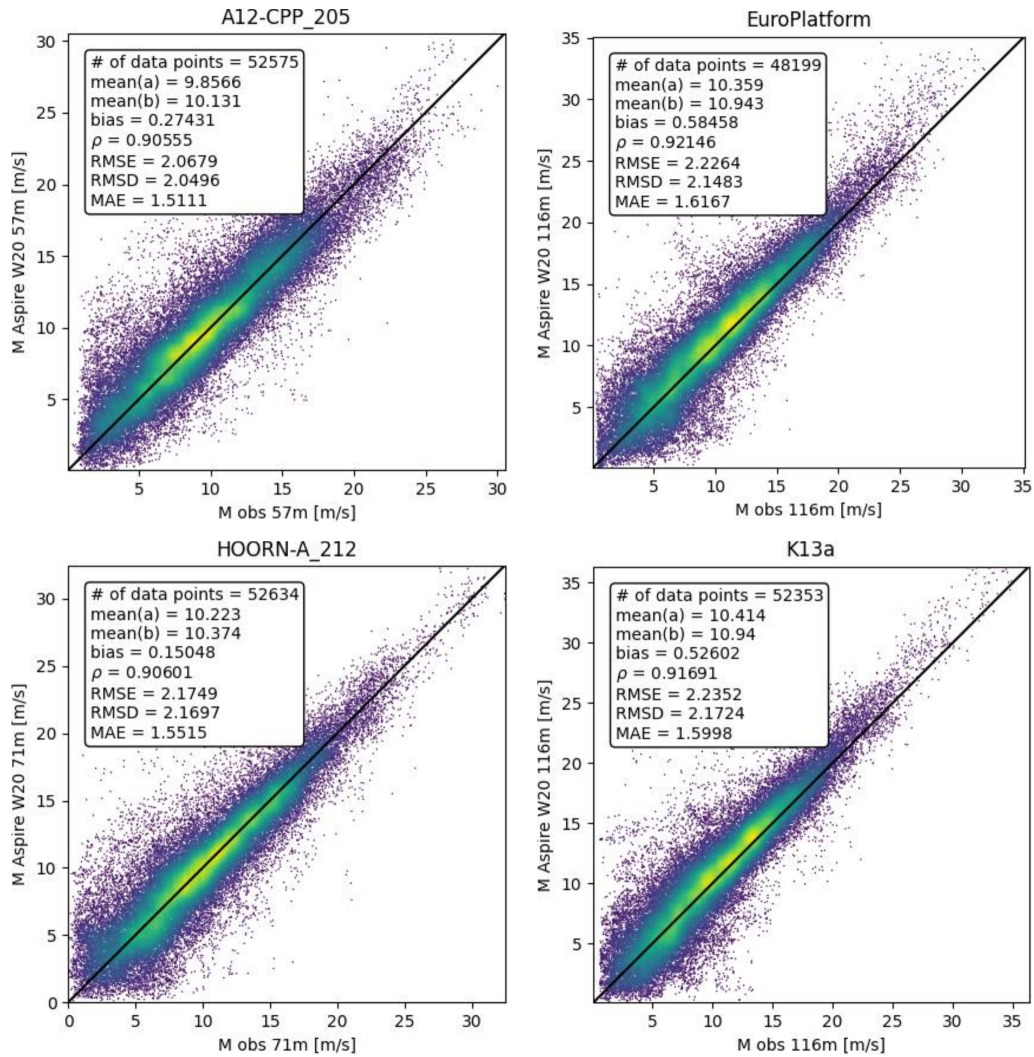


Figure 8. Wind speed performance metrics for several offshore measurement locations for the year 2020 based on 10-minute time records.

Using a separate ASPIRE simulation on a smaller domain, [Dirksen et al., 2023] studied wake effects for the wind farm site of Eemshaven. They showed the benefits of using high-resolution LES simulations for a complex coastal site. In a validation against LiDAR measurements, they showed that ASPIRE accurately captures nearby wake effects (Fig. 9).

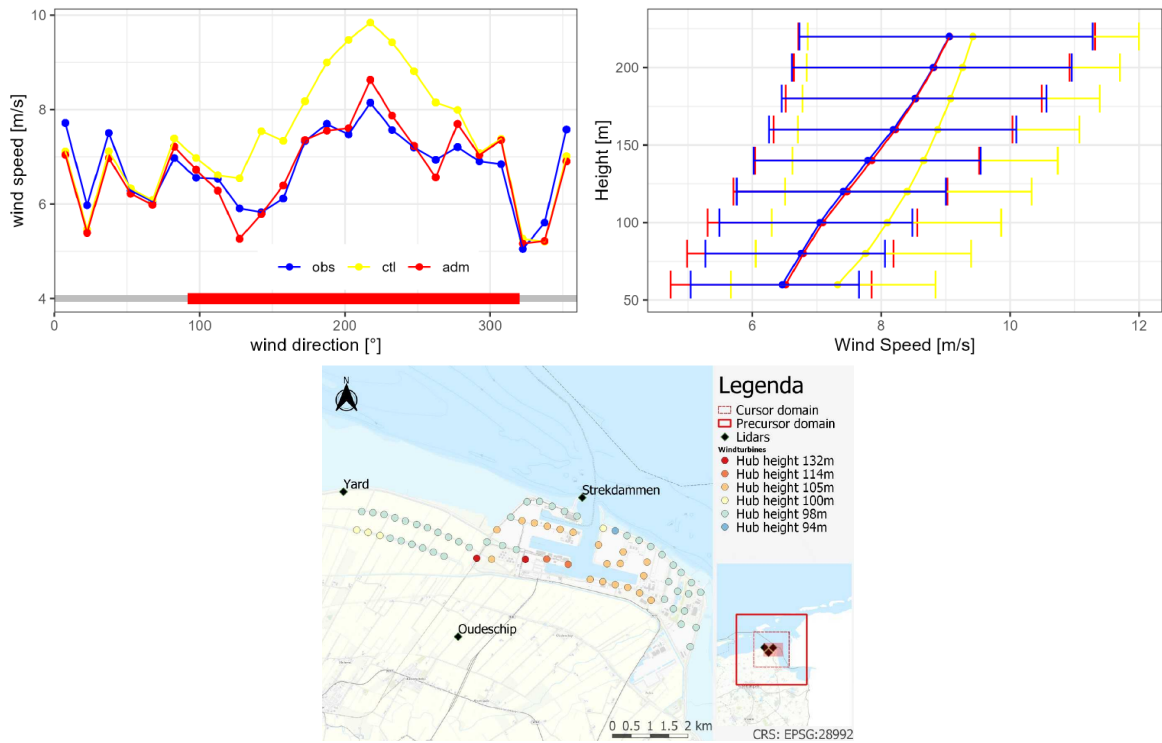


Figure 9. ASPIRE validation around the Eemshaven wind farm site. The top-panels show directional bias (left) and mean vertical profiles (right) at the Strekdammen location. Blue lines represent the observations, yellow lines a control simulation without wind turbines, and red lines the simulation with all wind turbines included. The bottom-panel shows a map of the simulated area.

6.3 The impact of a 2050 capacity scenario on the atmosphere

With the WINS50 simulations of a hypothetical 2050 capacity scenario, the impact of a large-scale expansion of offshore wind energy on the atmosphere can be assessed. The Image Library on the WINS50 website (www.wins50.nl/imagelibrary) provides a large number of preprocessed images from the HARMONIE-AROME simulations. With this website, users can easily explore the impact of both the present-day and the 2050 capacity scenarios on wind speed, temperature, and humidity. Images are available for different height, directional sectors and stability classes. Also, wind speed distributions are available for many locations in the domain. Daily (both 0 and 12 UTC) snapshots of the 100 m wind field can be viewed as well.

As an example, Fig. 10 shows the 2020 omni-directional 100 m wind speed difference between the HARMONIE-AROME W20 and W50 scenario simulations and the CTL simulation. While in the 2020 scenario wind farm wakes are limited, in the 2050 scenario the wind speed is reduced significantly over extensive areas. Obviously, the strongest reduction of wind speed occurs within the wind farms themselves.

Still, the omni-directional wind speed deficits of Fig. 10 do not tell the entire story as wind farm wakes are a downstream phenomenon. Therefore, Fig. 11 shows 100 m velocity deficits for two opposite 30-degree wide directional sectors. Compared to Fig. 10, the maximum wind speed reduction is larger, and the wakes extend much further downstream of the wind farms. It appears that on average wind farm wakes extent tens of kilometers. Depending on conditions, individual wakes can propagate much further as can be seen in the mentioned Image Library and, for instance, in [Wijnant and Stepek, 2023].

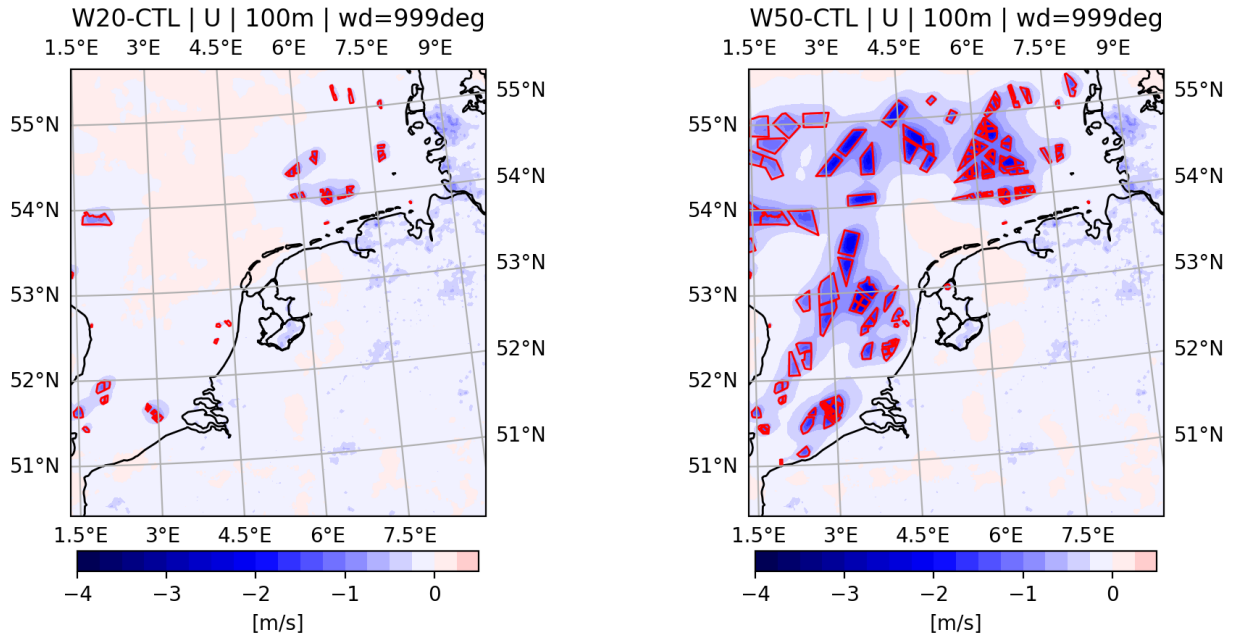


Figure 10. Mean wind speed difference (100 *m*) between the HARMONIE-AROME simulation with the present-day (W20) scenario and the undisturbed (CTL) simulation (left). Mean wind speed difference (100 *m*) between the simulation with the hypothetical 2050 scenario (W50) and the undisturbed (CTL) simulation (right).

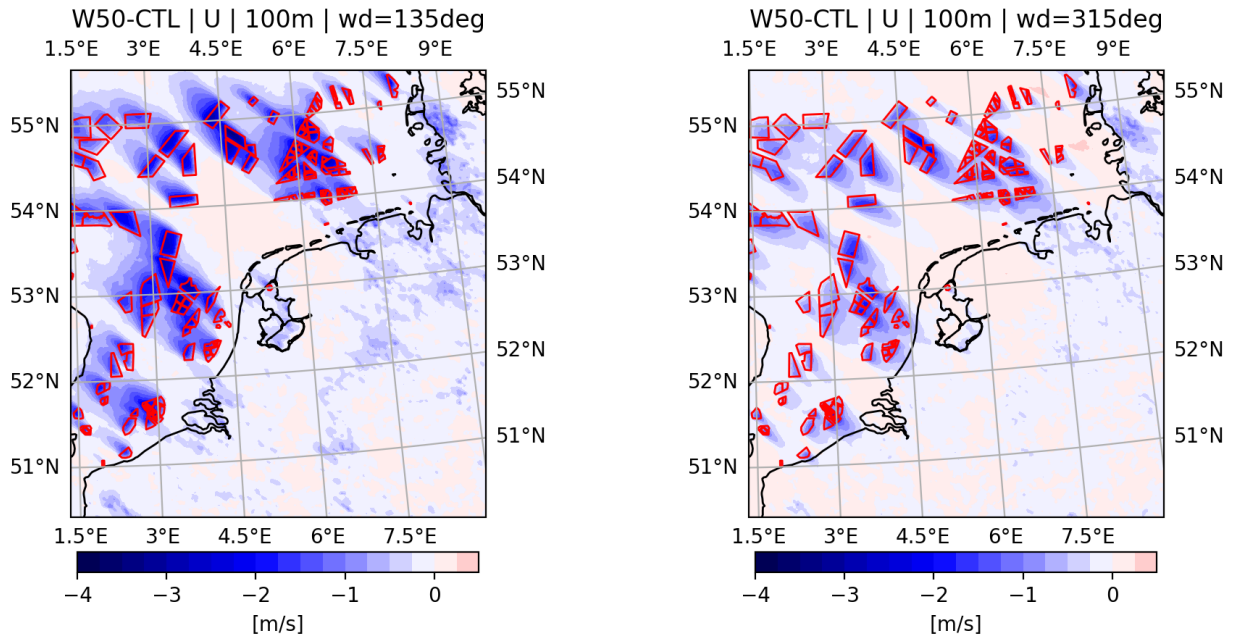


Figure 11. Mean wind speed difference (100 *m*) between the HARMONIE-AROME W50 simulation and the CTL simulation. Left: only including wind directions between 120 and 150 degrees. Right: only including wind directions between 300 and 330 degrees.

Figure 12 explores the offshore area fraction for which the 100 *m* velocity deficit of the HARMONIE-AROME W20 and W50 simulations is larger than a certain threshold value. Also, the impact of stability is shown. Data are stratified into stability classes based on thresholds of the bulk Richardson number between 100 and 10 *m* for a representative location in the North Sea. Three classes are defined: the 33.3% most unstable cases, the 33.3% most 'neutral' cases, and the 33.3% most stable cases.

Obviously, the affected areas are much larger in the W50 scenario than in the W20 scenario. In the W50 scenario on average 1/3 of the North Sea has a velocity deficit larger than 0.5 m/s , which is already a significant value. For larger threshold values the size of the affected area decreases. In stably-stratified conditions the wake-affected area is roughly twice as large as in unstable conditions. Similar findings were reported by [Zoe, 2021] who analyzed HARMONIE-AROME simulations with a future offshore energy capacity scenario over the German Bight.

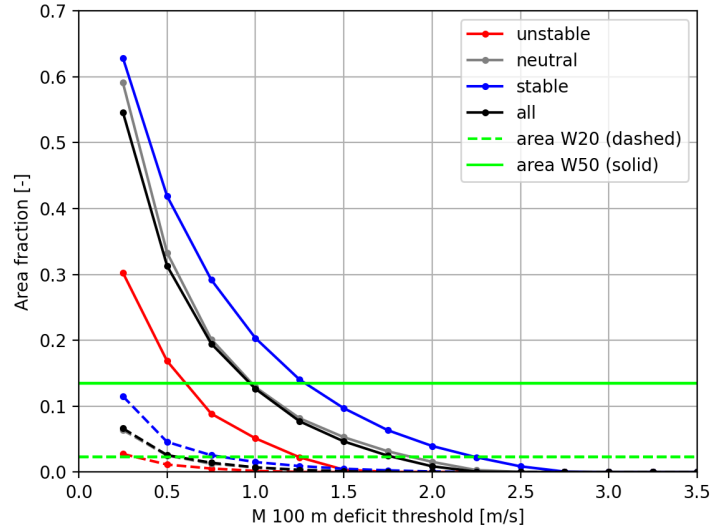


Figure 12. Offshore area fraction for which the 100 m wind speed velocity deficit of the HARMONIE-AROME W20 and W50 simulations is larger than a certain threshold value. Different colors represent different stability classes. Solid lines give the W50 fractions, dashed lines the W20 fractions. The horizontal lines indicate the area fractions occupied by the wind farms themselves.

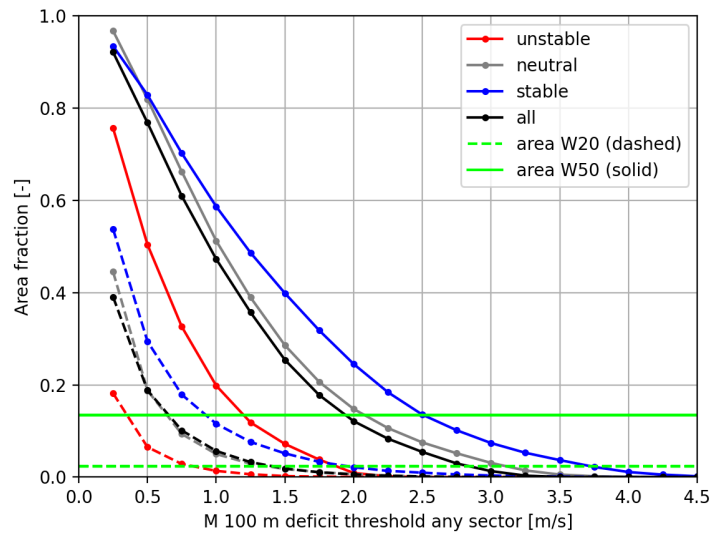


Figure 13. As Fig. 12, but showing the offshore area fraction for which the 100 m wind speed velocity deficit of the HARMONIE-AROME W20 and W50 simulations is larger than a certain threshold value for *any of 12 30-degree wind direction sectors*.

As wind farm wakes are a directional phenomenon, Fig. 13 presents a variation on Fig. 12. This time, it shows the offshore area fraction for which the 100-m wind speed velocity deficit of the HARMONIE-AROME simulations is larger than a certain threshold value but for *any of 12 30-degree wind direction sectors*. In other words, for a certain threshold value, 1 minus the presented area fraction is equal to the area fraction that is not affected by wind farm wakes for any of the 12 wind direction sectors. For instance, in the 2050 scenario only 25% of the North Sea will be unaffected by mean velocity deficits of 0.5 m/s for all wind directions. These numbers may be relevant for finding locations that require undisturbed wind conditions.

Inspection of the vertical profiles for grid points that are located within a wind farm, provides more insights on the impact of a large-scale rollout of wind energy on the atmosphere. Figure 14 shows mean difference profiles (W50-CTL) for wind speed (M), wind direction (phi), air temperature (Ta) and specific humidity (qv). Colors represent classes of stability. Within wind farms, the wind speed is reduced to a height of 400-500 m, most strongly for stably-stratified conditions. For wind direction, temperature and humidity the impact is small for unstable conditions. For stable conditions the wind direction is 'backed' (rotated counterclockwise) with respect to the control simulation. Near the ground a warming and drying of the air occurs, while at higher levels a cooling and moistening takes place. This can be understood from the strong gradients that exist for these variables in the control simulation for stable conditions. For unstable conditions gradients in temperature and moisture are already small, so additional mixing by wind turbines has only little effect.

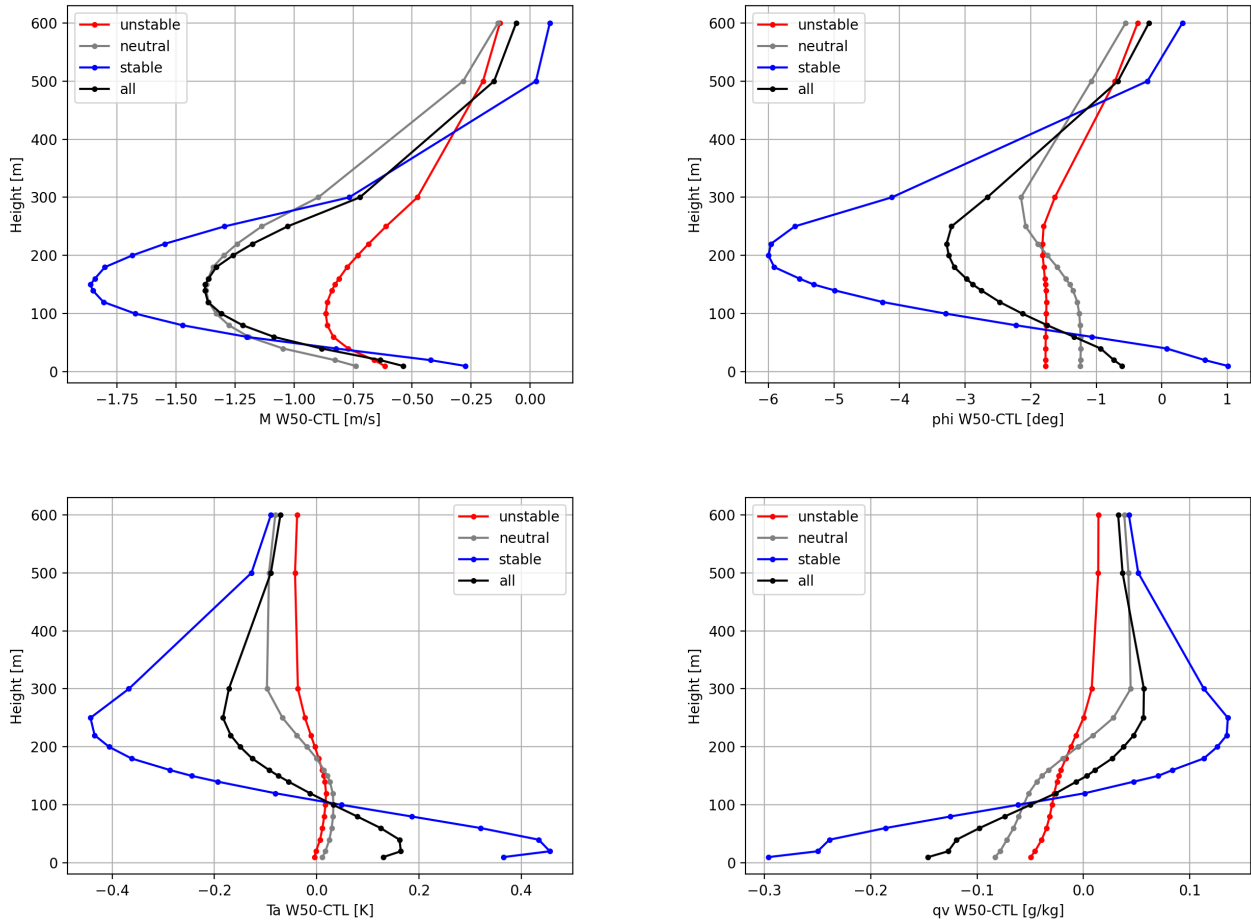


Figure 14. Mean differences in wind speed (M), wind direction (phi), temperature (Ta), and specific humidity (qv) between the simulation with the 2050 scenario (W50) and the undisturbed control simulation (CTL). Only grid points that include wind turbines are included. Colors indicate classes of stability.

A similar analysis has been applied to the ASPIRE simulations. As for ASPIRE no control simulation is available, we examine the difference between the W50 and the W20 simulation. Figure 15 shows vertical profiles for all virtual metmasts that are located within a 2050 wind farm, but not in a 2020 wind farm (for clarity, only the lowest 3 km of the domain are shown). Although differences exist, similar patterns as in the HARMONIE-AROME simulations are seen. In addition, the

results suggests that because of the additional wind farms in the W50 scenario the liquid water content of the lower atmosphere increases, which corresponds to increased cloudiness. Also, the wind speed variance and the momentum flux show increased values for the 2050 scenario.

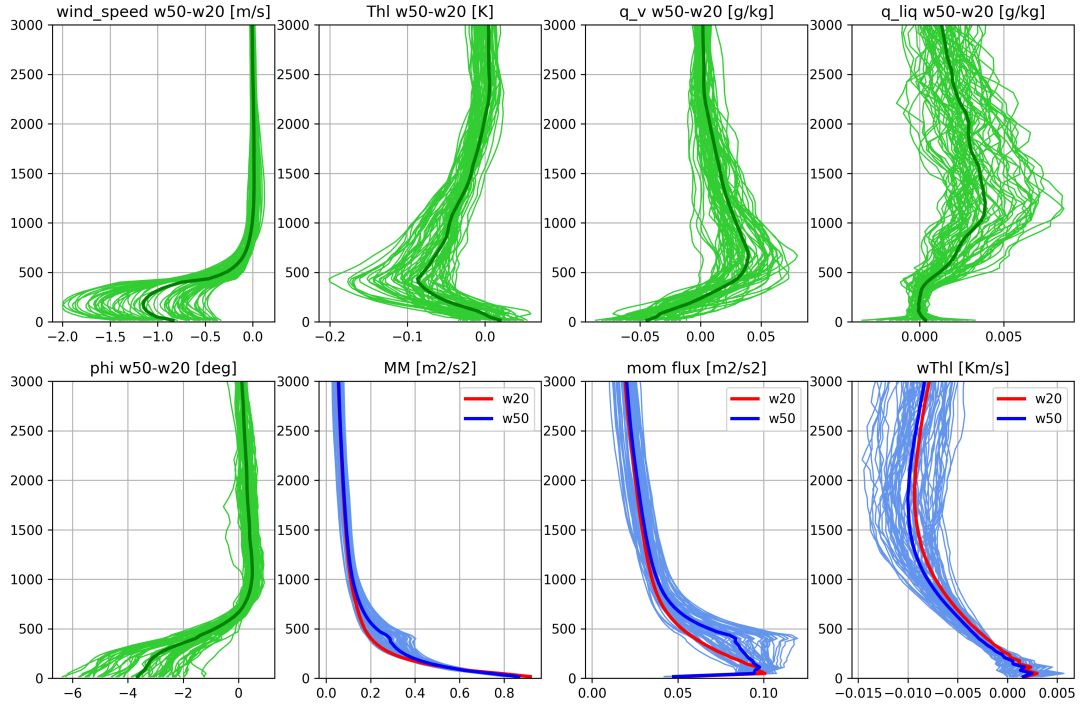


Figure 15. Mean vertical profiles from ASPIRE for virtual metmasts that are within a W50 wind farm, but not in a W20 wind farm. Thin lines indicate individual virtual metmasts, thicker lines indicate average values.

It is illustrative to compare the mean wind fields from HARMONIE-AROME and ASPIRE. Figure 16 shows that the spatial patterns in both W50 simulations show close correspondence, but that the wind speeds in ASPIRE are higher.

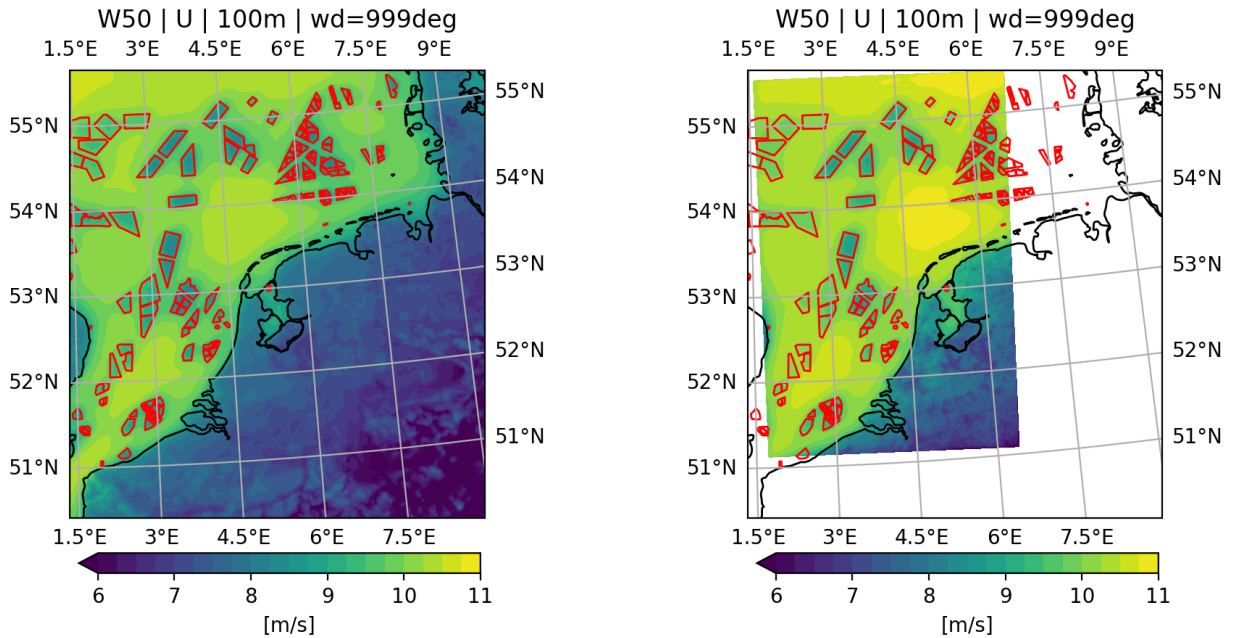


Figure 16. Mean 100 m wind speed from the HARMONIE-AROME (left) and the ASPIRE (right) 2050 scenario simulations.

When considering the wind speed difference between the W50 and the W20 simulation (i.e. additional wake-induced velocity deficits) differences between HARMONIE-AROME and ASPIRE are small. This is shown in Fig. 17. Spatial patterns are comparable and difference in the modeled velocity deficits are small.

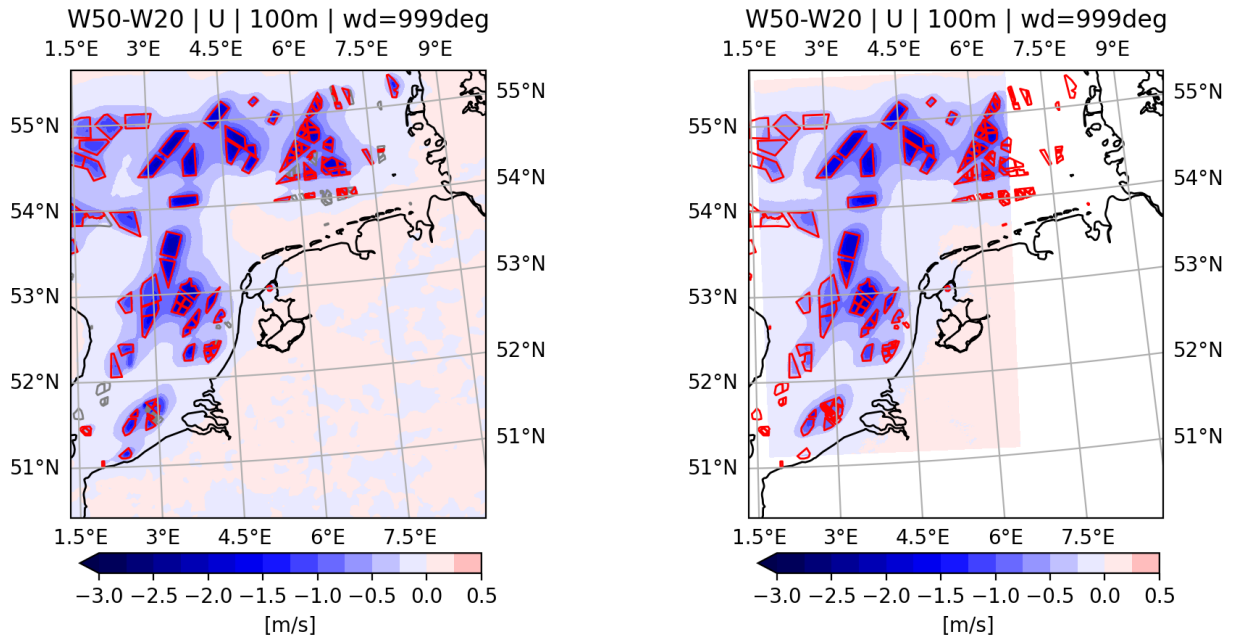


Figure 17. Mean 100 *m* wind speed velocity deficits (W50-W20) from the HARMONIE-AROME (left) and the ASPIRE (right) 2050 scenario simulations.

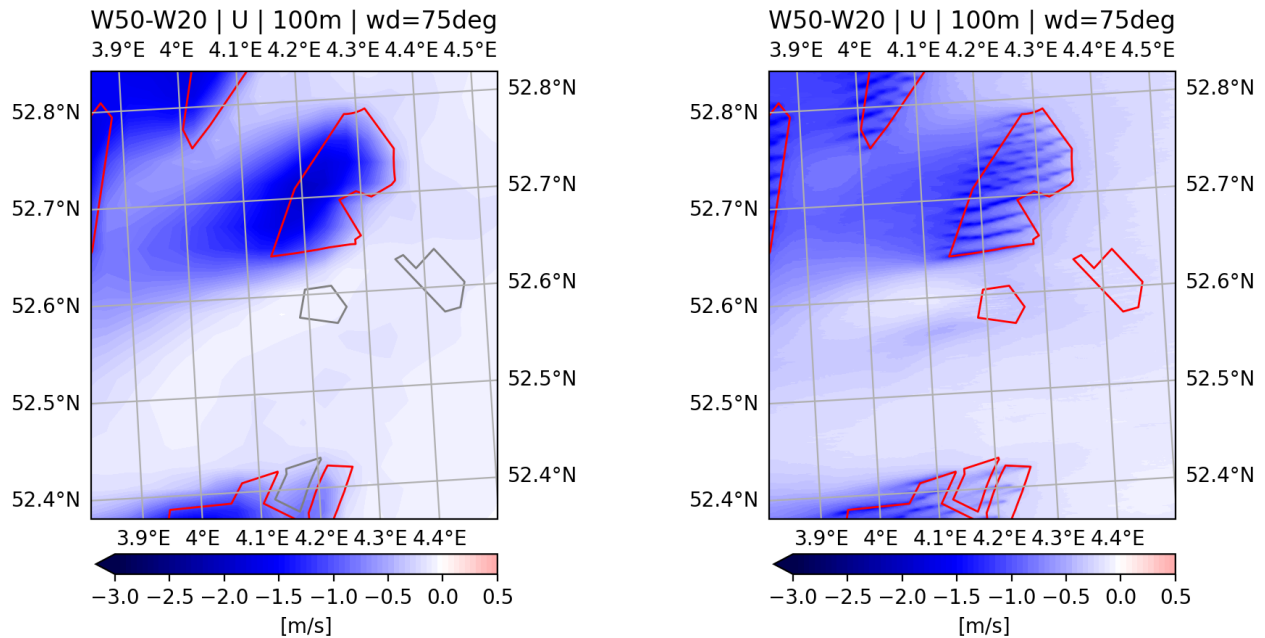


Figure 18. Mean 100 *m* wind speed deficit (W50-W20) from the HARMONIE-AROME (left) and the ASPIRE (right) 2050 scenario simulations (northeasterly winds only) for an area in front of the Dutch coast. In the ASPIRE deficit field the locations of individual turbines can be recognized.

Looking at Figs. 16 and 17, the level of detail in the ASPIRE simulations is easily overlooked. Therefore, Fig. 18 shows a

zoom of an area in front of the Dutch coast for northeasterly wind directions. This illustrates the difference in detail between the 2.5 km HARMONIE-AROME grid and the 128 m ASPIRE grid.

6.4 The 2050 scenario and energy production

Increasing the installed energy capacity will lead to increased energy production. However, wind farm efficiency may go down as wake effects become more and more important. To start with the former, focusing on the wind farms in the Dutch Exclusive Economic Zone (EEZ) only, Fig. 19 (left panel) shows the total modeled energy production for the present-day scenario and the 2050 scenario for both the HARMONIE-AROME and the ASPIRE simulations. The 2020 production is only around 2% of the future 2050 scenario.

A different view is presented in the right panel of Fig. 19, which shows the efficiency of the installed wind farms by means of the capacity factor. Here we define the capacity factor as the ratio between the realized production and the rated (installed) production. The vast expansion of the installed capacity results in a lower energy capacity factor. The production and capacity factors of the ASPIRE simulation are higher than those of the HARMONIE-AROME simulations. The main factor to understand this difference is probably the higher wind speed in the ASPIRE simulation (cf. Fig. 16. Difference in the turbine modeling will likely play a role, as well. Further research is needed to obtain a better understanding of the differences between the models.

At this point, it is tempting to compare the results of Fig. 19 with formal energy production scenarios. Depending on the technological and societal developments, two pathways are currently envisaged in The Netherlands for the year 2050 (e.g. [Rijksoverheid, 2024]). The first scenario, with an installed capacity of 38 GW, assumes an energy production of 170 TWh per year (capacity factor of 0.510). With an installed capacity of 72 GW, the second scenario assumes a yearly production of 325 TWh (capacity factor of 0.515). Comparison of the implied capacity factors in the energy projections with the capacity factors as modeled by the WINS50 2050 scenario indicates the former are not unrealistic. However, arguments can be made that the capacity factors given by the model simulations are too high for being long-term representative: first, the simulated year 2020 has a higher than average wind speed (Fig. 1) and second, both the HARMONIE-AROME and ASPIRE simulations have a positive bias (Figs. 7 and 8). Furthermore, it should be noted that in the model simulations the turbines are always 'active' and power production only depends on atmospheric conditions. However, in reality additional losses will occur due to turbine failures, curtailment events, and regulations related to birds/bats migration episodes.

The WINS50 project was primarily set up as a research project to study interactions between the atmosphere and a future wind farm scenario. For obtaining more detailed insights into the production and efficiency of specific scenarios (e.g. for 2030, or for 2050 with 38 or 72 GW installed capacity), additional model simulations are required.

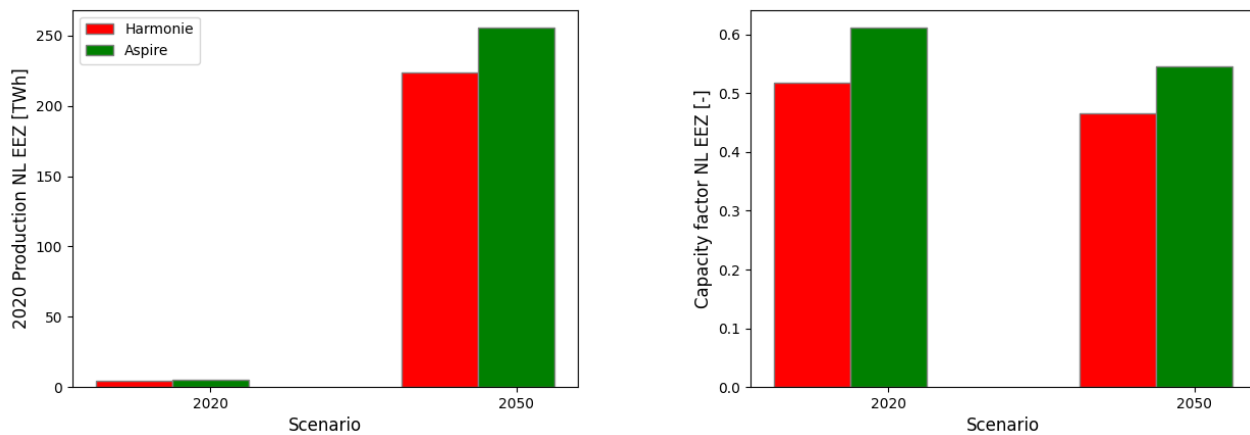


Figure 19. Total energy production in TWh (left) and capacity factors (right) for the Dutch EEZ as modeled by HARMONIE-AROME and ASPIRE.

Fig. 20 shows the spatial distribution of the capacity factor for the HARMONIE-AROME present-day and 2050 scenarios. Again, in the 2050 scenario, capacity factors are reduced. In the 2050 scenario (right panel) the interior of the wind farms have the lowest capacity factors. Also, the capacity factors of the UK wind farms are generally higher than those of the Dutch and German wind farms. This is because the installed capacity density (MW per square kilometer) is generally lower in the UK wind farms.

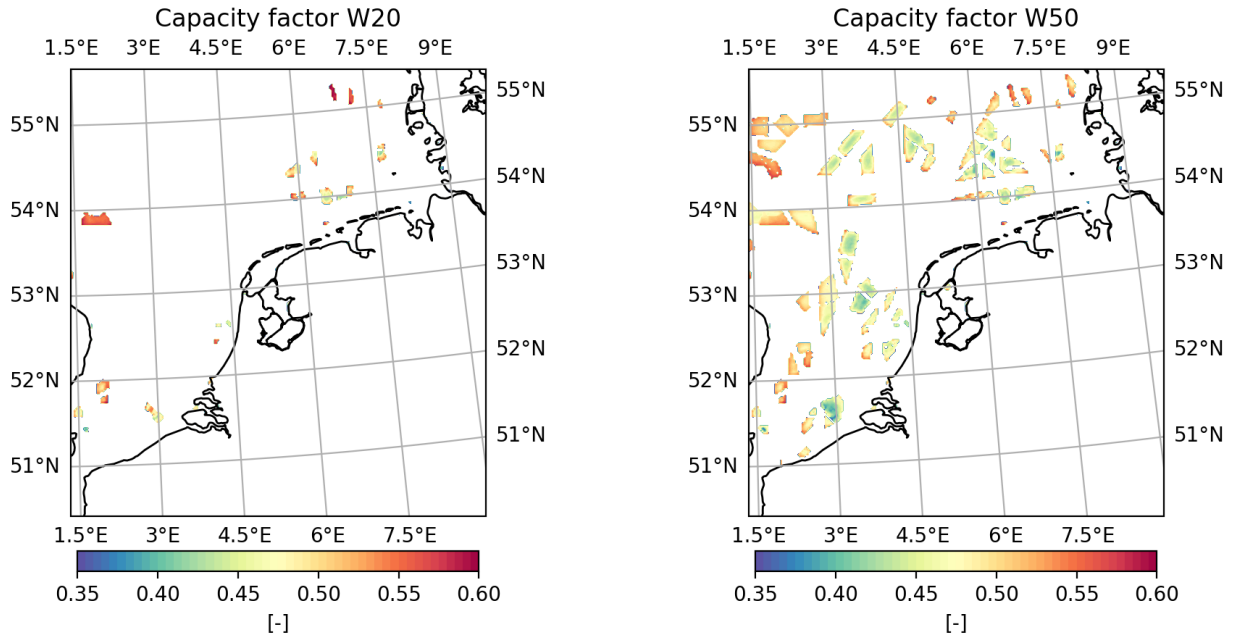


Figure 20. Capacity factors for the HARMONIE-AROME 2020 (left) and 2050 (right) scenarios.

To stress the dependency of the capacity factor on the ambient conditions, Fig. 21 shows the variation of the capacity factor over the year. The much lower values in summer are simply related to a lower wind speed. Modest changes in wind speed can have a significant impact on the power production.

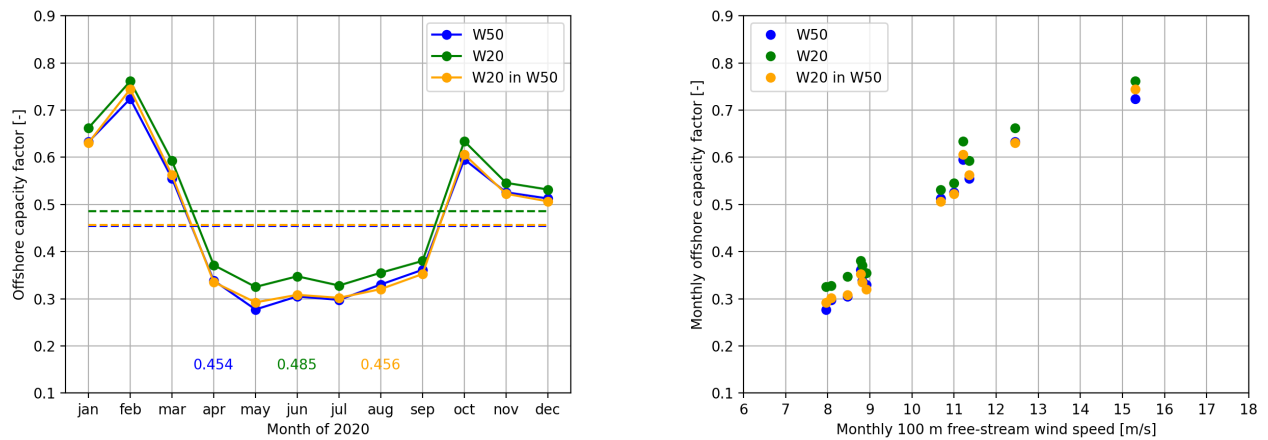


Figure 21. Monthly capacity factors for the HARMONIE-AROME simulations (left). Relation between the monthly (2020) offshore capacity factors and the monthly mean (in space and time) offshore 100 *m* wind speeds derived from the HARMONIE-AROME control simulation (right).

Next, we inspect the energy production of the wind farms that are present in both the operational 2020 scenario and the future 2050 scenario. For each present-day '2020' wind farm, the difference between the two simulations indicates the impact of the additional future wind farms in the 2050 simulation. Numbers based on the ASPIRE simulations are shown in Fig. 22. On average, the production of the 2020 goes down by 6 to 7%, but large differences among wind farms exist. Wind farms which remain relatively isolated in the 2050 scenario experience much lower production losses than wind farms that are facing large additional wind farms in their surroundings (e.g. in the German Bight or the Belgian wind farm cluster). From the map, it also seems that wind farms with a high turbine density are more prone to additional losses.

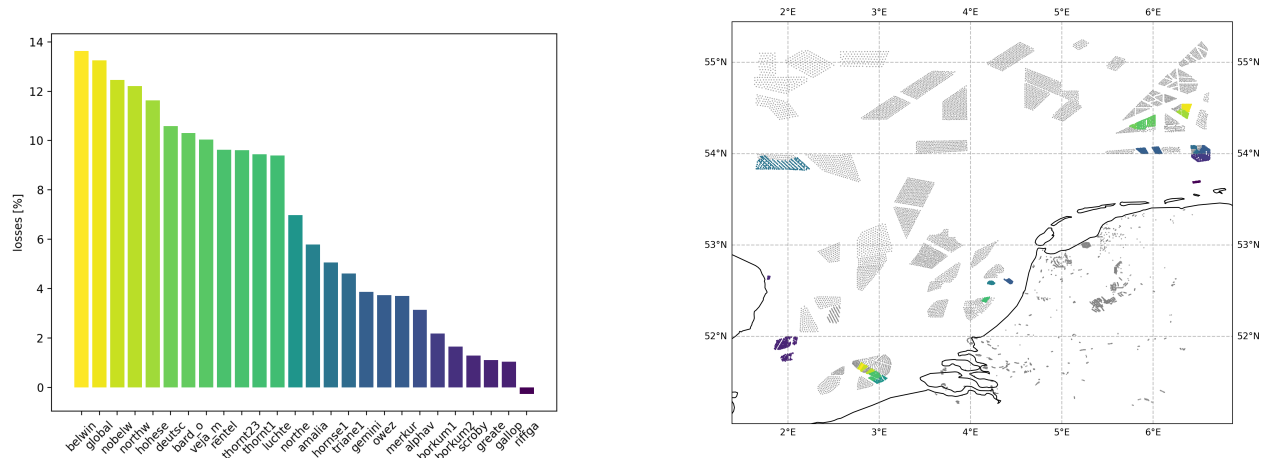


Figure 22. Production decrease of the 2020 wind farms in the 2050 scenario simulation in ASPIRE (left). Map of wind farms (right) with the color coding of the 2020 wind farms corresponding to the decrease in production as indicated in the left panel.

Finally, we compare the additional losses of the 2020 wind farms in the 2050 scenario as modeled by HARMONIE-AROME and ASPIRE. As shown in Fig. 23, a clear correlation exists between the results of the two models. For the wind farms with the most significant production losses in the 2050 scenario, HARMONIE-AROME gives larger values than ASPIRE.

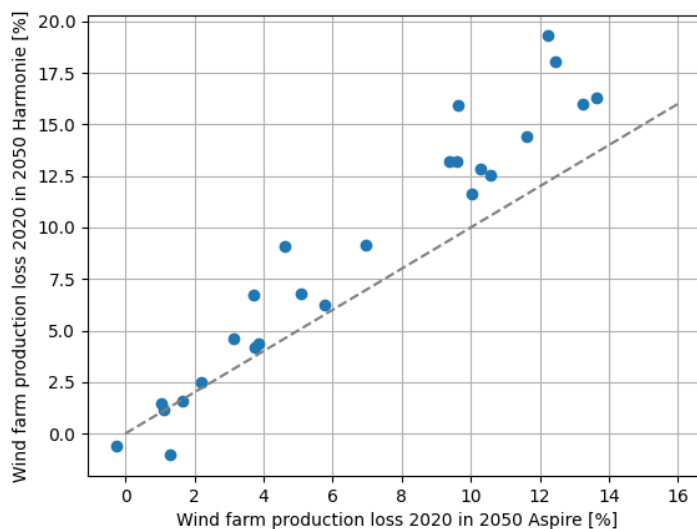


Figure 23. Additional losses of 2020 wind farms in the 2050 scenario. HARMONIE-AROME versus ASPIRE.

7 Work package 6 — Sensitivity studies

7.1 Introduction

In addition to the long-term simulations with a present-day and a future 2050 capacity scenario, several sensitivity studies have been carried out within the WINS50 project. In this Section the main findings are summarized. In particular, the following topics are addressed:

- The impact of capacity density and turbine type on production (Sect. 7.2)
- Impact of neighboring wind farms on the IJmuiden Ver wind farm zone (Sect. 7.3)
- The limit of an infinitely large wind farm (Sect. 7.4)

7.2 Impact of capacity density and turbine type

Using ASPIRE, [Baas et al., 2023] investigated the energy production and wake losses for multi-gigawatt offshore wind farms. To that end, one year of actual weather from 2015 was simulated for a suite of hypothetical 4 GW offshore wind farm scenarios. The scenarios differed in terms of applied turbine type, installed capacity density, and layout. Free-stream production numbers were obtained from an additional simulation that contained drag-free turbines that do produce power but do not exert drag on the flow.

The results suggest that production numbers increase significantly when the rated power of the individual turbines is larger while keeping the total installed capacity the same. Even for turbine types with similar rated power but slightly different power curves, significant differences in production were found. This is summarized in Fig. 24, which shows power production and aerodynamic losses (i.e. the sum of losses related to global blockage and internal wake losses) for each of the six scenarios.

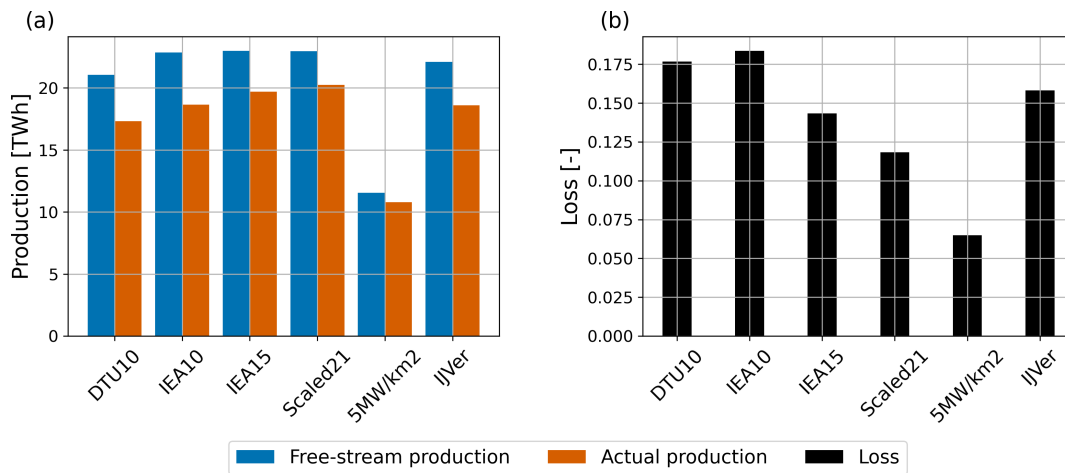


Figure 24. Free-stream and actual power production (left) and aerodynamic losses (right) for six 4 GW offshore wind farm scenarios.

For all considered scenarios, 80% of the aerodynamic losses occur in a narrow wind speed range of 8 to 12 m/s. On the other hand, 50% of the energy production occurs without any aerodynamic losses when all turbines operate at rated capacity. Although wind speed is identified as the most important factor determining aerodynamic losses, [Baas et al., 2023] were able to isolate the impact of stability. A fair assessment of this impact seemed possible by only considering wind speeds between 6 and 10 m/s. In this wind speed range, aerodynamic losses may be 10 percentage points larger for stably-stratified conditions compared to convective conditions (Fig. 25).

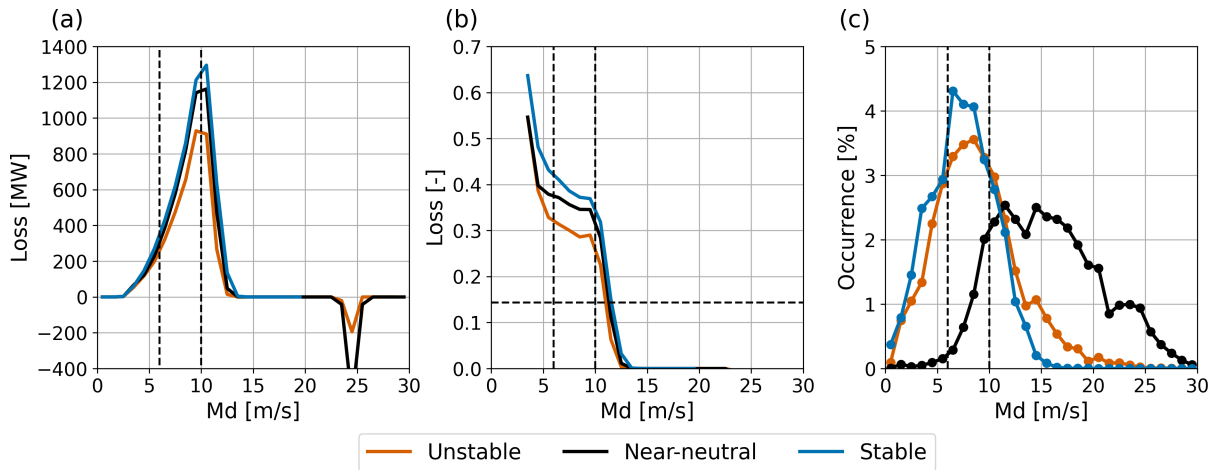


Figure 25. Combined effect of wind speed and stability on wind farm aerodynamic losses for the IEA15 scenario. (a) Power losses in megawatts (MW). (b) Relative aerodynamic losses. (c) Frequency of occurrence of the three stability classes. Dashed lines at 6 and 10 m/s indicate the wind speed interval for which the aerodynamic losses are relatively constant. The horizontal dashed line in (b) indicates the overall aerodynamic loss.

Inspection of spatial variations over the 4 GW wind farms shows interesting patterns. Fig. 26 shows aerodynamic losses, mean wind speed, and velocity deficit compared a free-stream equivalent for northeasterly flow direction for the IEA15 scenario. Wake losses vary significantly within the 4 GW wind farm. Along the sides of the wind farm significant flow accelerations are visible. Already upstream of the wind farm the wind speed is reduced (global blockage effect, see e.g. [Bleeg et al., 2018], [Schneemann et al., 2021], [Sanchez Gomez et al., 2023]). As a result of the blockage effect, in this example the first-row turbines (i.e. those facing 'free-stream conditions') produce up to 10% less power than if they had operated in isolation.

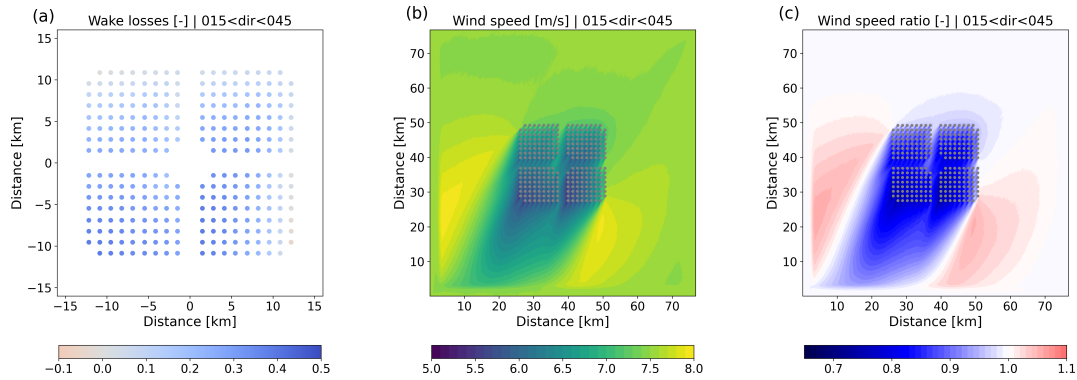


Figure 26. Aerodynamic losses (a), mean 140 m wind speed (b), and ratio of actual to free-stream wind speed (c) for a hypothetical 4 GW offshore wind farms for northeasterly winds.

For their study, [Baas et al., 2023] did not use the ASPIRE version used for the 2020 and 2050 capacity scenarios as described in Sect. 3, but an earlier version that applied periodic boundary conditions in combination with applying dynamic tendencies derived from ERA5.

7.3 Impact of neighboring wind farms on the IJmuiden Ver wind farm zone

A second sensitivity study (using the same version of ASPIRE as used in Section 7.2) explored the impact of neighboring wind farms on the production of the 4 GW IJmuiden Ver wind farm zone ([Baas and Verzijlbergh, 2022]). A comparison was made between production numbers from a one-year ASPIRE simulation (2015) with the IJmuiden Ver wind farm in isolation versus those of a simulation with all surrounding wind farms included (Fig. 27). Results of both simulations were compared to free-stream production numbers derived from an additional simulation with drag-free turbines.

The modeling results indicate that the energy production of the future wind farm of IJmuiden Ver may experience significant production losses from wake effects of upstream wind farms. On a yearly basis the production deficit could amount to 4%. For wind speeds between 6 and 12 m/s this number increases to 10%. The production deficits resulting from upstream wind farms show a strong dependency on wind direction.

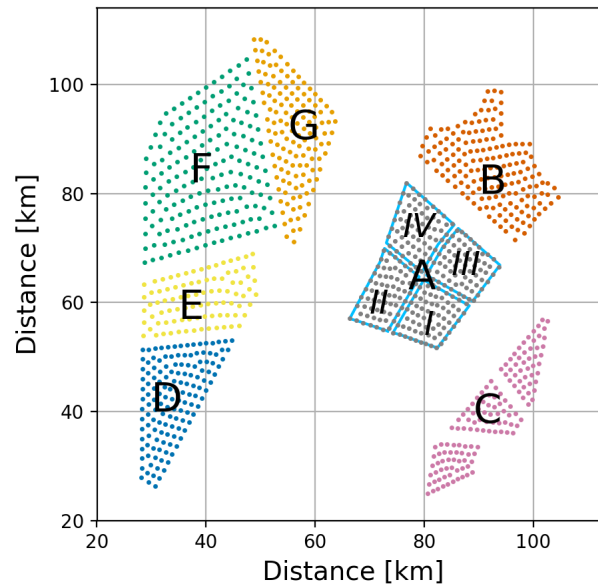


Figure 27. Layout of the ASPIRE IJmuiden Ver study.

7.4 Infinite wind farm

The WINS50 2050 scenario simulations show mean capacity factors of around 0.5 (Fig. 19). At the same time, in the interior of large 4 to 5 GW wind farms much lower capacity factors are observed (Fig. 20). A natural question is what the energy production would be in the limit of an infinite wind farm. What is the maximum amount of momentum that the atmosphere or boundary layer can supply from above to replenish the energy taken out of the flow by a very large wind farm (e.g. see [Calaf et al., 2010], [Miller et al., 2015], [Possner and Caldeira, 2017])?

In the framework of WINS50, several model simulations have been done to explore these questions. With HARMONIE-AROME a 3-month (April - June 2020) simulation was performed with the entire North Sea filled-up with 15 MW turbines with an capacity density of 8 MW/km^2 . The installed capacity of this gigantic wind farm was 3000 GW .

In addition, four year-long simulations (2020 meteorology) with ASPIRE were performed on a small, 12.3 km domain. The domain was filled with 15 MW turbines at a capacity density of 3.6, 8.0, and 12.0 MW/km^2 , respectively. A fourth simulation without active turbines was performed to obtain free-stream conditions. This free-stream simulation contained drag-free turbines that do produce power but do not exert drag on the flow. As such, they provide reference, 'free-stream' production numbers. Periodic boundary conditions were applied so that wakes leaving the domain entered the domain at the opposite site, thus mimicking effectively an infinite wind farm.

Figure 28 shows the 10 m wind speed for the HARMONIE-AROME WINS50 2050 scenario simulation and the simulation with the North Sea filled-up with wind turbines compared to the WINS50 control simulation. Obviously, the wind speed is seriously reduced in case of such a hypothetically large wind farm. Even over land a significant decrease in 10 m wind speed occurs (in contrast to the 2050 scenario).

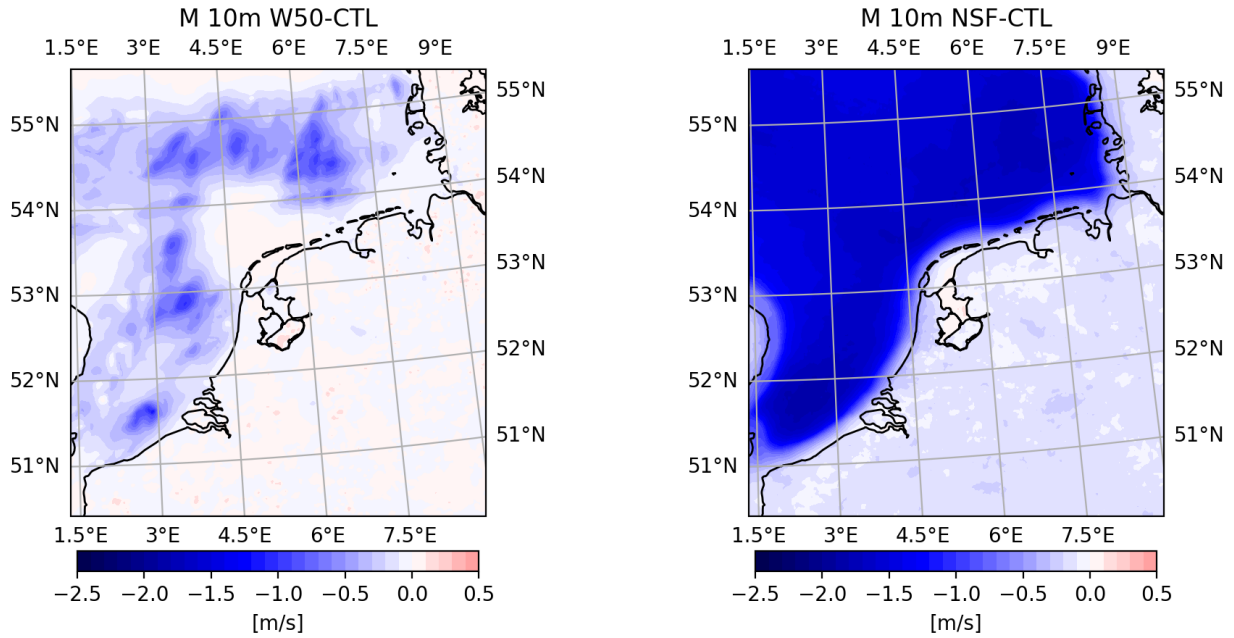


Figure 28. Mean HARMONIE-AROME 10 *m* wind speed reduction for the WINS50 2050 scenario simulation (left) and for the simulation with the North Sea filled-up with turbines (right) compared to the WINS50 control simulation.

The capacity factor of the North Sea filled-up simulation is shown in Fig. 29, together with the capacity factor of the WINS50 2050 scenario for the corresponding 3-month period of April - June (note that the latter are much lower than the year-round values, cf. Figs. 20 and 21). While in the northern parts of the North Sea the capacity factor is as high as 0.30, in the southern North Sea this decreases to values around 0.2. Comparison with the capacity factor of the 2050 scenario it seems that values in the central parts of the larger wind farms / wind farm clusters are not that much higher than in the simulation with the entire North Sea filled-up. This suggests that already in the WINS50 2050 scenario internal wake effects deep in the modeled wind farms are approaching the limits of an infinite wind farm.

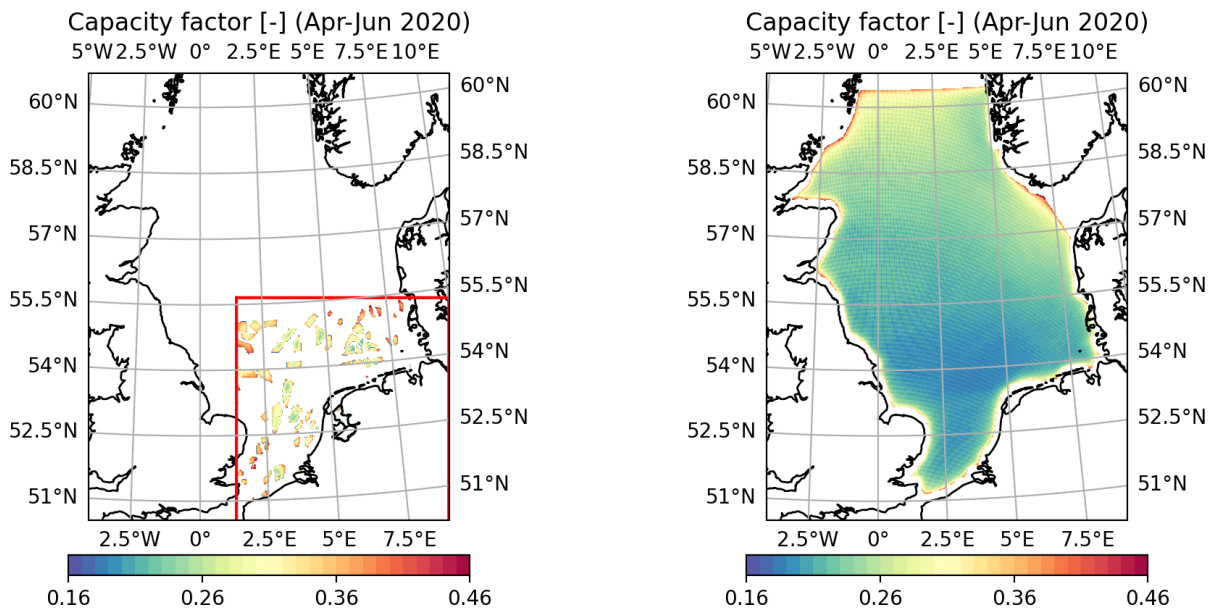


Figure 29. Capacity factor for the WINS50 2050 scenario simulation (left, only April-June) and for the simulation with the North Sea filled-up with turbines (right).

Production numbers and aerodynamic losses from the three ASPIRE 'infinite' wind farm simulations are shown in Fig. 30. As expected, the free-stream production per turbine is the same for each of the capacity density scenarios (around 9.5 MW). At the same time the actual production decreases with increasing density capacity. Converted to production per square kilometer, the free stream production increases proportionate with the installed capacity density. Also the actual production per square kilometer increases with capacity density, but less than proportionate. This is reflected in the aerodynamic losses, which increase from around 20% in case of the 3.6 MW/km² scenario to 55% in case of 12.0 MW/km² scenario.

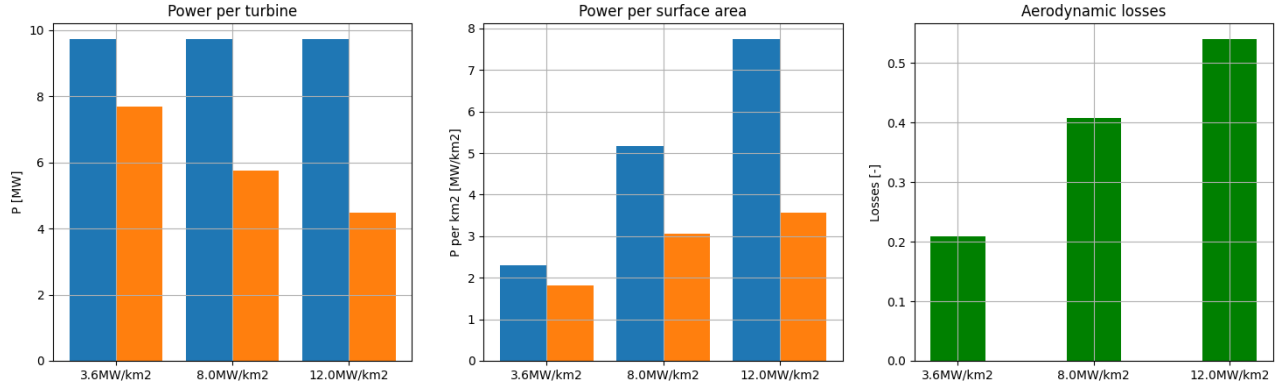


Figure 30. Free-stream (blue) and actual (orange) production numbers for 'infinite' wind farms with varying capacity density (left and middle panel). Corresponding aerodynamic (wake) losses (green) are presented as well (right panel).

It is interesting to inspect the dependency of the production as a function of free-stream wind speed (Fig. 31). With increasing density, stronger and stronger free-stream winds are required to reach rated power production. While the rated wind speed of the applied IEA 15 MW reference turbine is 11 m/s, the 12 MW/km² reaches only rated power at free-stream wind speeds well over 20 m/s. When doing so, this scenario does indeed produce 12 MW/km². The lower density scenario saturated already for lower wind speeds and will eventually produce less energy. When considering the total energy production as a function of wind speed, thus combining the production of each wind speed bin with the frequency of occurrence, it appears that most energy is produced at around 14 m/s.

Figure 31 shows that there is not something like an absolute limit in the vertical downward transport of energy (for strong enough winds even the scenario with the densest capacity reaches rated power). Obviously, the efficiency of this 12 MW/km² scenario is very low. On the other hand, Fig. 31 indicates that for a given wind speed the available energy is indeed limited: for the lower wind speeds the production per square kilometer is close together for the three scenarios. In practice, the optimal density will be determined by a trade-off between efficiency requirements and the local wind climate.

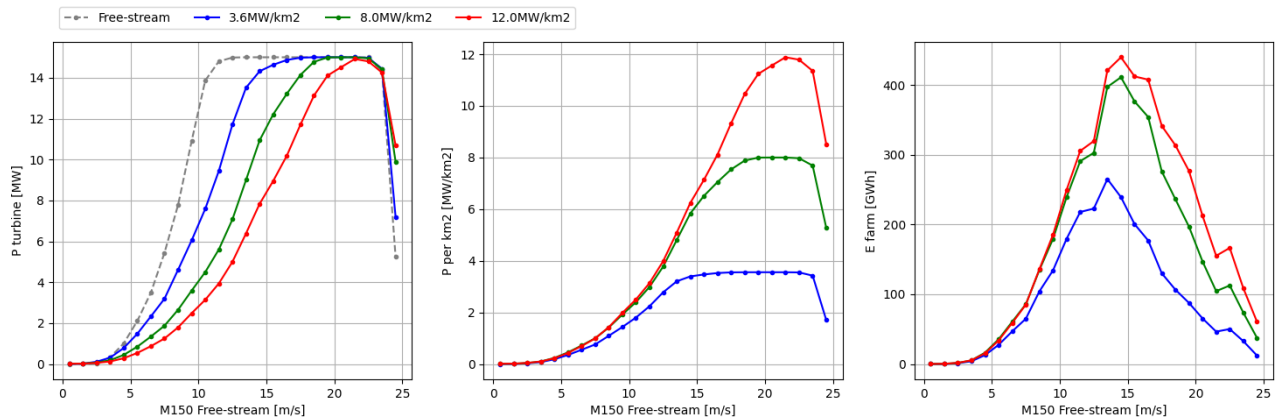


Figure 31. Production per turbine (left), production per square kilometer (middle), and total 2020 energy production (right) as a function of the 150 m free-stream wind speed for the three ASPIRE 'infinite' wind farm scenarios.

Finally, Fig. 32 presents vertical profiles (annual means) of a suite of meteorological variables for the three capacity densities and the free-stream simulation (for clarity, only the lowest 3 km of the 9 km domain are shown). Clearly, there is a major impact on the wind. Besides a seriously reduced wind speed at the height of the turbines, a modest speed-up at elevated

levels occurs. Also, a strong backing of the wind is observed with respect to the free-stream simulation. The wind farm induced vertical momentum transport also impacts the temperature and moisture profiles. Close to the surface a warming and drying occurs, at higher levels the opposite is observed. Interestingly, the amount of liquid water and the cloud fraction increase at the top of the boundary layer, but decrease closer to the surface. Increasing the capacity density leads to an increase of the vertical momentum transport, both in magnitude and in the depth of the affected layer.

The tendencies of the impact of the 'infinite' wind farms shown in Figure 32, corresponds very well with the impact of wind farms on the atmospheric profiles as modelled in the HARMONIE-AROME and ASPIRE WINS50 2050 scenarios (cf. Figs. 14 and 15).

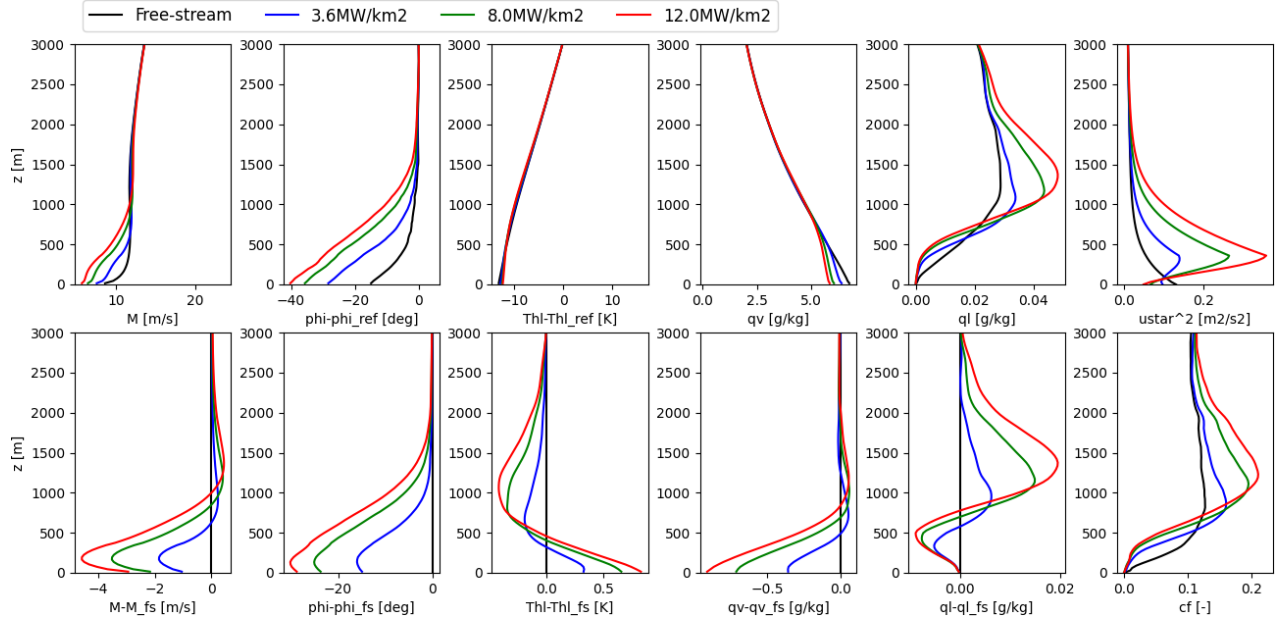


Figure 32. Annual mean profiles of wind speed (M), wind direction with respect to 3000 m (ϕ), vertical potential temperature with respect to 3000 m (Thl), specific humidity (q_v), liquid water (q_l), momentum flux (u_{star}^2), and cloudiness (cf). For wind speed, wind direction, potential temperature, specific humidity, and liquid water, the difference with the free-stream conditions are plotted as well.

8 Conclusions

In the WINS50 project the impact of a large-scale rollout of wind energy in the North Sea was investigated. To that end, simulations have been performed with state-of-the-art atmospheric models. With HARMONIE-AROME, the operational weather model of KNMI, two three-year (2019-2021) simulations were performed: one for undisturbed conditions (without wind farms) and one with operational wind farms included. Moreover, a one-year simulation of a hypothetical 2050 capacity scenario was carried out (using 2020 meteorology).

Within the WINS50 project, ASPIRE, Whiffle's Large-Eddy Simulation (LES) model, was transformed from a traditional LES model with periodic boundary conditions to a genuine weather model with prescribed boundary conditions. Using the acquired new capabilities of ASPIRE, one-year simulations for a present-day and for a 2050 capacity scenario were performed. The combination of the simulated area, the horizontal resolution of 128 m, and the covered time period make these simulations one of the most extensive LES simulations ever performed.

From both the HARMONIE-AROME and the ASPIRE simulations a wealth of meteorological and power production data have been made publicly available. Data can be downloaded with simple scripts. This allows researchers from meteorological and energy communities, as well as policy makers, to make their own analysis of a wake-affected future wind climate and energy production.

Research, done in the framework of the WINS50 project, indicates that in 2050 large parts of the North Sea will be affected by wind farm wakes. Vertical mixing arising from the wind farms will affect the vertical distribution of other variables as, for instance, temperature and moisture. Results indicate that cloud cover may increase as well. In line with earlier findings, these effects are stronger in stably-stratified conditions than in unstable (or convective) conditions. At the same time, no evidence was found that in a 2050 capacity scenario the wind climate over land will be significantly affected.

As a result of the increased amount of offshore wind farms, the efficiency of the wind farms will decrease compared to the present-day situation. Still, for the Dutch EEZ, the total energy production in relation to the installed capacity does not invalidate formal projections of future offshore energy production. Considering the wind farms in the future 2050 scenario that are also in the present-day scenario (basically the currently operational wind farms), results from both HARMONIE-AROME and ASPIRE suggest that their decrease in production may vary from 0 to almost 20%, depending on their location with respect to the additional wind farms in the 2050 scenario.

Sensitivity studies show that production numbers increase significantly when the rated power of the individual turbines is larger while keeping the total installed capacity the same (e.g. n times 20 MW turbines versus $2n$ times 10MW turbines). Even for turbine types with similar rated power but slightly different power curves, significant differences in production were found. A sensitivity study with virtually infinite wind farms provides insights in the limits of the production of offshore wind energy.

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