Wind farms in WINS50 climatology

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Content

1. Introduction

One of the aims of the WINS50 project[1] is to provide meteorological information for the years 2019, 2020, 2021 including the effect of operational wind farms on the atmosphere[2]. The WINS50 project also provides meteorological information for a hypothetical wind farm scenario in 2050 (for 2020 weather).

The hourly WINS50 meteorological data is based on HARMONIE-AROME[3] Cycle43h2.1 (referred to as HarmCy43 in this report) which is nested in ERA5 climatology[4]. WINS50 is made in the same way as the Dutch Offshore Wind Atlas DOWA (which is described in Innovations in the DOWA project | DOWA project | Dutch Offshore Wind Atlas), but in WINS50 we use HarmCy43 instead of Cycle 40h1.2. The difference in wind speed at hub height is small[5].

[1] The WINS50 project is executed by the project partners Whiffle, TU Delft and KNMI and supported with Topsector Energy subsidy from the Ministry of Economic Affairs and Climate Policy.
[2] WINS50 also provides climatology without wind farm effects (thus extending DOWA https://www.dutchoffshorewindatlas.nl/ with 3 years using HARMONIE-AROME CY43 instead of CY40) in order to be able to assess and validate the wind farm effect.
[3] https://journals.ametsoc.org/view/journals/mwre/145/5/mwr-d-16-0417.1.xml
[4] ERA5 | ECMWF
[5] MemoComparisonDOWAandWINS50.pdf

In section 2 of this report we describe how the effect of wind farms is modelled in HarmCy43 using the Fitch et al. [6] [7] Wind Farm Parametrization (WFP). The HARMONIE-AROME model that includes wind farm effects will be referred to as HarmCy43-WFP. The WFP uses wind turbine information (location, hub height, rotor diameter, power- and thrust curve) to modify the momentum and TKE tendencies in HARMONIE-AROME across the rotor of the turbine. This approach assumes that the wind turbines perform according to the turbine specific power and thrust curves. So poor performance (e.g. because turbines are old and not well maintained) or the fact that turbines are not always in operation despite that there is enough wind (e.g. because of maintenance or legislation to protect migrating birds and bats) are not taken into account.

The aim of this report is to summarise which wind farms and what turbine information is used in the simulations with operational capacity in 2019 (section 3), 2020 (section 4), 2021 (section 5) and to explain how we designed the scenario for 2050 (section 6).

2. Modelling wind farms in HARMONIE-AROME

2.1 Wind farm parameterisation

The Wind Farm Parameterisation (WFP) used in this research is based on the work of Blahak et al. (2010)[8], Fitch et al. (2012)[9] and Van Stratum et al. (2022)[10]. The parameterization introduces an elevated momentum sink on the mean horizontal flow, a source of electrical energy and a source of TKE as a result of nonproductive drag. The parameterisation assumes that the vertical wind component is unaffected by drag of the turbine blades and that drag of the turbine tower is negligible. Drag of the turbine blades is modelled as a force that is constant across the rotor area but depends on 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: it varies between 17%-75% (Fitch et al., 2012). C_T and C_p depend on the turbine type. Their dependence on atmospheric stability is neglected (Platis et al., 2018) and a first order approximation is used. The difference between the extracted energy from the atmosphere and the electricity produced is assumed to be the TKE produced. Thereby, mechanical and electrical loss components are assumed to be negligible.

The nature of the parameterisation is such that it assumes the wind turbines are an order of magnitude smaller than the grid size. Therefore, the model accounts for the influence of the total amount of turbines in one grid cell (Van Stratum et al., 2019). 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. A detailed description of the WFP and the functions it

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[6] Fitch et al. Local and Mesoscale Impacts of Wind Farms as Parameterized in a Mesoscale NWP Model. Mon Weather Rev, 140(9):3017–3038, ISSN 00270644, 2012.

[7] https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2021MS002947

[8] Blahak U, Goretzki B and Meis J (2010) A simple parameterization of drag forces induced by large wind farms for numerical weather prediction models. EWEC 6(1):4577–4585

[9] Fitch, A. C., Olson, J. B., Lundquist, J. K., Dudhia, J., Gupta, A. K., Michalakes, J., & Barstad, I. (2012). Local and mesoscale impacts of wind farms as parameterized in a mesoscale NWP model. Monthly Weather Review, 140(9), 3017–3038. https://doi.org/10.1175/mwr-d-11-00352.1

[10] Van Stratum, B., Theeuwes, N., Barkmeijer, J., van Ulft, B., & Wijnant, I. (2022). A one-year-long evaluation of a wind-farm parameterization in HARMONIE-AROME. Journal of Advances in Modeling Earth Systems, 14, e2021MS002947. https://doi. org/10.1029/2021MS002947

solves can be found in the work of Fitch et al. (2012) and Van Stratum et al. (2022) mentioned earlier in this section.

2.2 How wind farms are included in the model

To be able to run HarmCy43-WFP we need turbine locations and information on the turbine types (e.g. hub height, rotor diameter, thrust (C_T) and power (C_P) curves). Turbine locations for offshore wind farms were obtained from combining several publicly available data sources (see 2.2.1). When only the wind farm boundary (shape file with outline of the wind farm) and the total number of wind turbines per wind farm were available, we used an iterative repulsion method was used to get a uniform distribution of wind turbines over the shape of the wind farms. That the exact location of the turbines is not known was not a problem because within the WFP all turbines are aggregated to the nearest 2.5 × 2.5 km HarmCy43 grid point (Stratum et al, 2022).

We distinguish between 'present' wind farms (up to April 2021), 'planned' wind farms (roughly up to 2030) and 'future' (2050) wind farms.

2.2.1 'Present' wind farms

For the 'present' wind farms (sections 3, 4 and 5) we used four data sources (all with their own pros and cons[11]) to obtain the required turbine information (location, hub height, power and thrust curve) for the WFP: (1) EMODnet (only offshore, no individual turbines, free), (2) OpenStreetMap (worldwide, but no turbine types and not always accurate, free), (3) WindStats.nl (only Netherlands, not free) and (4) TheWindPower (Europe only onshore, only one location per wind farm, missing key variables, not free).

The locations, hub heights, and turbine types of the offshore wind farms are determined by combining EMODNet[12] (shapefiles with outline of wind farms) and open street map data (location of individual turbines). The turbine locations in the Netherlands are purchased from WindStats and the locations in the rest of the domain from The Wind Power.

Following Van Stratum et al. (2022), the C_P and C_T curves were obtained from various sources, predominantly from the windPRO input database (Acker & Chime, 2011). For a small number of turbines, no C_P and C_T curves were publicly available. Those turbines have been replaced with either reference data from literature, or C_P and C_T curves from similar turbines. Turbine hub heights are derived from different sources on the internet.

Appendix B provides an overview of the wind farms that were included in the 2019 in the HarmCy43-WFP simulation, including information on the turbines. The shape file that is used can be found on the WINS50 website (https://wins50.nl/downloads/wins50_windfarm_scenarios.zip).

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[11] https://www.umr-cnrm.fr/accord/IMG/pdf/accord_wfpapril2021.pdf

[12] *The European Marine Observation and Data Network* (EMODnet); Frontiers | The European Marine Observation and Data Network (EMODnet): Visions and Roles of the Gateway to Marine Data in Europe (frontiersin.org).

2.2.2 ‘Planned’ wind farms

The wind farm sites of the ‘planned’ wind farms are as realistic as possible. Table 1 lists the wind farms on which information was available on wind farm capacity and turbine type. We assumed 10MW wind turbines (DTU_10MW_178RWT_v1) and a capacity density of 8 MW/km^2 if no information was available. Turbine specifications for DTU_10MW_178RWT_v1 were taken from https://nrel.github.io/turbine-models/Offshore.html (e.g. hub height 119m).

Name Wind Farm	Capacity	Turbines (MW)
Noordhinder Noord	700	15
Noordhinder Zuid	1400	15
Seamade (Seastar)	250	10
Seamade (Mermaid)	240	10
HKN	759	10
HKW	2100	
- kavel VI	700	15
- kavel VII	700	15
- kavel VIII	700	15
HKZ	1540	
- kavel 1	450	10
- kavel 2	320	10
- kavel 3	290	10
- kavel 4	480	10
Ten Noorden vd Wadden	700	15
Ijmuiden Ver	6500	
- kavel 1	1000	15
- kavel 2	1000	15
- kavel 3	1000	15
- kavel 4	1000	15
- Ij_ver_noord	2500	15
Dogger Bank A	1200	10
Dogger Bank B	1200	10
Dogger Bank C	1200	10
Doggers Bank South West	1500	15
Doggers Bank South East	1500	15
East Anglia Hub One North	798	10
East Anglia Hub Two	910	10
East Anglia Hub Three	1400	10
Hornsea Project 2	1386	10
Hornsea Project 3	2400	10
Hornsea Project 4	2160	10
Norfolk Boreas	1800	10
Norfolk Vanguard (east)	900	10
Norfolk Vanguard (west)	900	10
Outer Dowsing	1500	15
Sofia	1400	10

Table 1. Overview of planned wind farms for which actual installed capacity was implemented in WINS50-2050 scenario. Belgian wind farms (green), Dutch wind farms (orange) and UK wind farms (blue).

2.2.3 'Future' wind farms

Because the WINS50-project focusses on offshore, we have not considered a future scenario for the onshore wind farms: the 2050 scenario for onshore wind farms is the same as in HarmCy43-WFP for 2020 (section 4) and the onshore turbines are the ones present on 1-1-2020. Also, we assume that the 'present' wind turbines are not replaced by 2050, which is off course not realistic with an average wind turbine life span of about 20 years, but allows for direct comparison of the two wind farm simulations.

The 'future' offshore wind farms are based on the hypothetical wind farm scenario of the WOZEP North Sea ecosystem study for 2050 [13] [14], but not entirely the same. In this memo we will refer to the 2050 wind farm scenario used by WOZEP as the 'WOZEP-2050 scenario' and to the 2050 wind farm scenario used in WINS50 as the 'WINS50-2050 scenario'.

Figure 1 shows the (hypothetical) **WOZEP-2050 scenario**. This scenario is based on:

- The national targets for 2050 that were available in 2020 based on the PBL "Samen duurzaam" scenario (IV)[15] published in 2018 (which was 60GW offshore installed capacity in Dutch waters)[16]
- A capacity density in future wind farms of 8 MW/km^2. This is slightly more than assumed in the PBL "Samen duurzaam" scenario (IV), which assumes 4-6 MW/km^2. In contrast, the most recent plans of the Dutch government apply a capacity density of 10 MW/km^2 [17].
- Maximum wind farm size: $400km^2$
- The fact that international shipping lanes and Natura 2000 areas are not available for offshore wind farms (military areas, sand mining areas, fishing-grounds, bird fly-zones and important areas for seals are not a priori excluded)

Figure 2 shows the (hypothetical) **WINS50-2050 scenario**. The Dutch windfarms in the WINS50-2050 scenario are based on actual site locations ("kavels"), rather than the "wind farm zones" (areas that might be used for offshore wind energy) that were used in WOZEP. Just to clarify: these "kavels" are in the "wind farm zones", but do not take up the whole area of the "wind farm zone" [18]. The site locations are from the RVO Offshore wind energy road map from April 2021, which is already changed significantly at the time of writing this report (figure 3). The "kavels" are filled with wind turbines using the iterative repulsion method described in section 2.2.

So the main differences between the WOZEP-2050 scenario and the WINS50-2050 scenario are that (1) WOZEP-2050 uses "kavels" instead of "wind farm zones" and (2) planned capacity density and turbine types (instead of the default WOZEP capacity density of $8MW/km^2$) for some of the planned wind farms in Belgium, the Netherlands and the UK. More detailed information on the differences between the WOZEP-2050 scenario and the WINS50-2050 scenario can be found in appendix A.

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[13] Goal WOZEP: impact large-scale offshore wind energy on growth of phytoplankton, the foundation of the aquatic food web. https://www.noordzeeloket.nl/en/functions-and-use/offshore-wind-energy/ecology/offshore-wind-ecological-programme-wozep/reports-on-ecosystem-research/@247549/2021-bottom-up-potential-ecosystem-effects-large/

[14] Van Duren et al.: Ecosystem effects of large upscaling of offshore wind on the North Sea - Synthesis report. 11203731-004-ZKS-0010, Deltares, Delft, 2021

[15] De toekomst van de Noordzee | PBL Planbureau voor de Leefomgeving

[16] The target in 2022 is 38-72GW

[17] The most cost-efficient wind farms in the North Sea are operating at a capacity density of $5MW/km^2$. Further increasing the capacity density increases the power production, but also the price of production due to higher wake losses. However, this does not mean that most wind farms on the North Sea have a $5MW/km^2$ capacity density. The capacity density of UK wind farms is e.g. generally much lower (about 2.5 MW/km^2). The Dutch Government considers $10MW/km^2$ and even $15MW/km^2$ because of limited space on the North Sea with areas designated as shipping lanes, nature reserves and fishing grounds or for the military.

[18] https://offshorewind.rvo.nl/

Just like for the 'planned' wind farms we assumed a capacity density of 8 MW/km^2 for the 'future' wind farms, but we used 15MW turbines (IEA_15MW_240RWT) instead of 10MW turbines. Turbine specifications are from https://nrel.github.io/turbine-models/Offshore.html (e.g. hub height 150m).

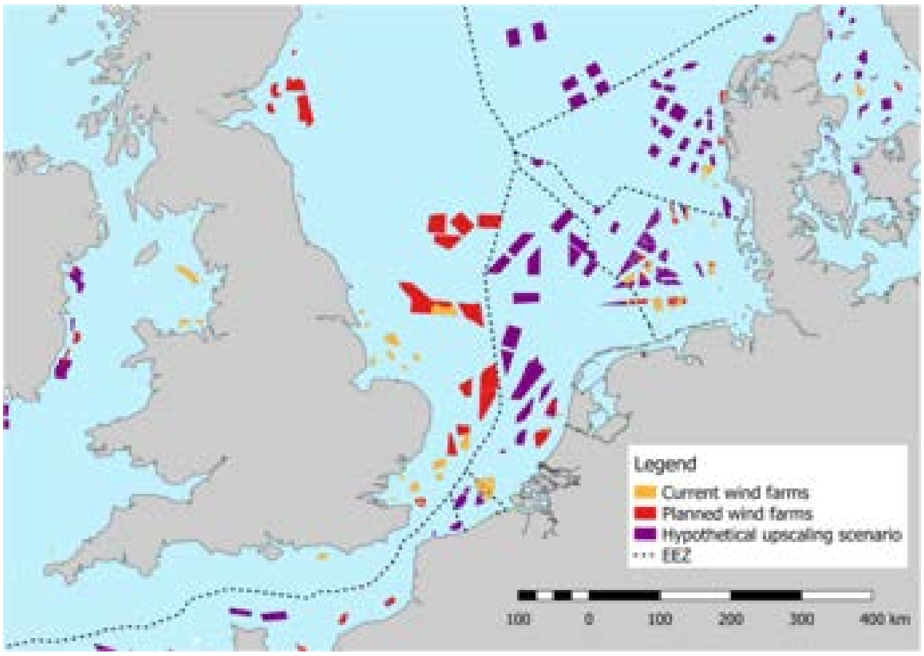

Figure 1: hypothetical wind farm scenario for 2050 in WOZEP study (WOZEP-2050 scenario)[19]

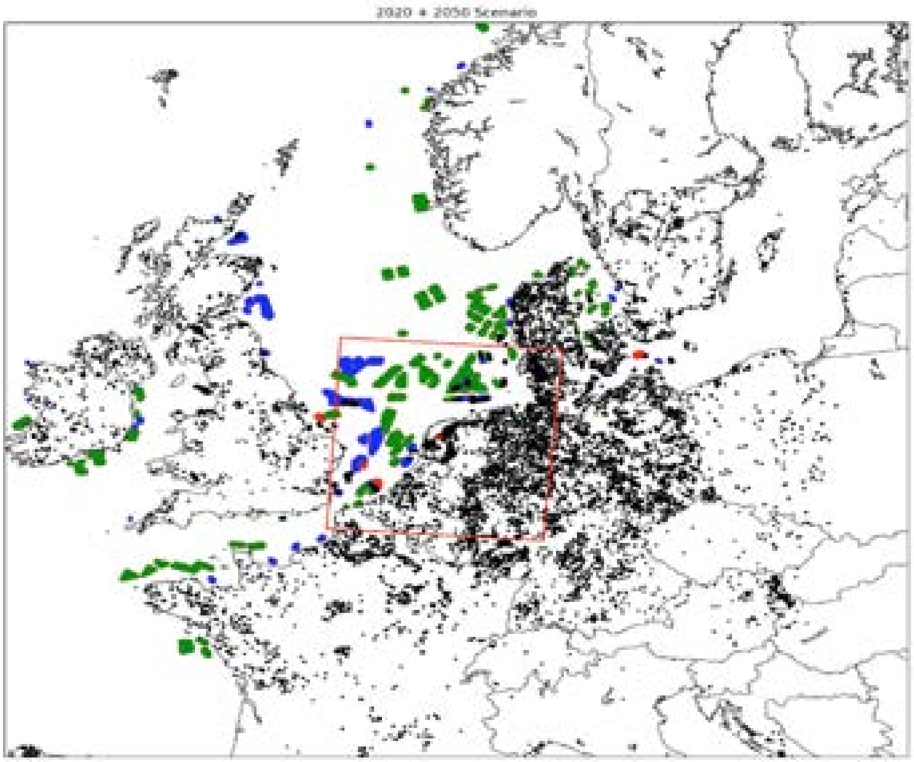

Figure 2: hypothetical wind farm scenario 2050 in WINS50 study (WINS50-2050 scenario). In black wind farms 1-1-2020, red wind farms built between January 2020 and April 2021, in blue (10MW) and green (15MW) planned wind farms.

[19] synthesis-ecosystem-effects-of-large-upscaling-of-offshore-wind-on-the-north-sea (7).pdf

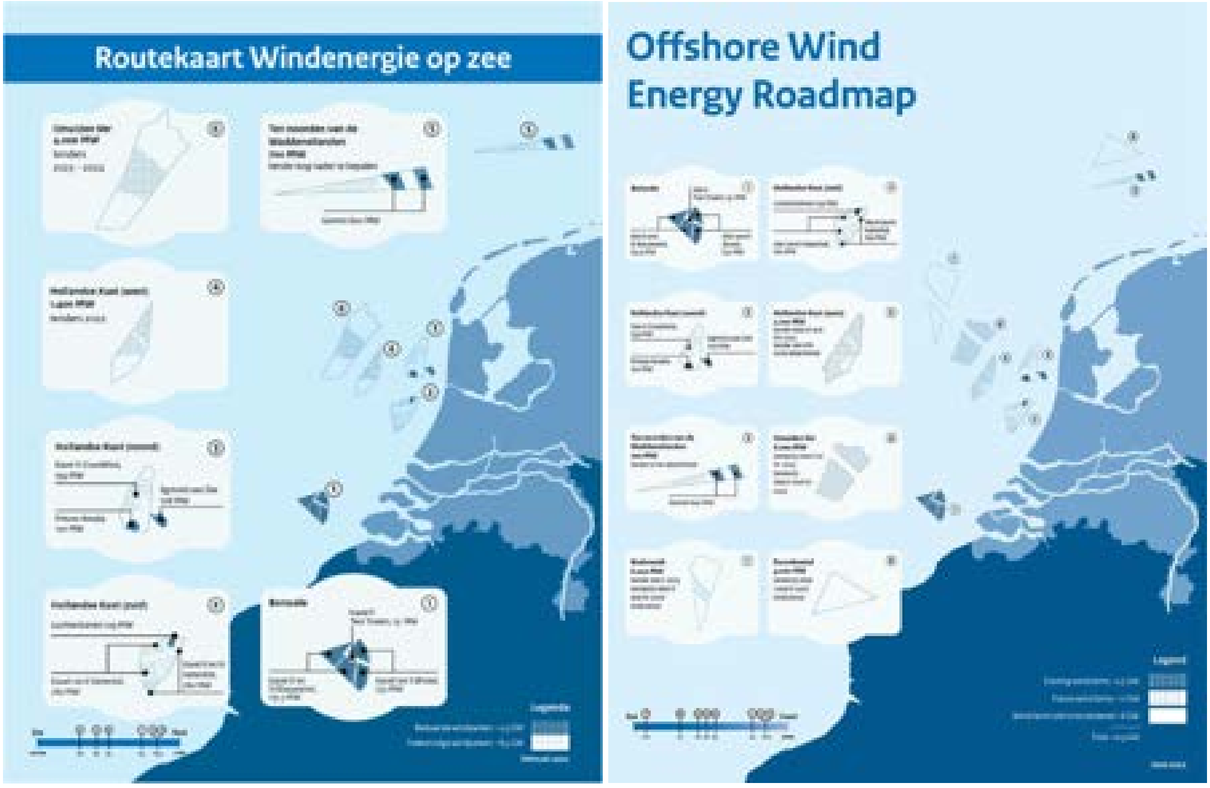

Figure 3: Offshore wind energy road map from April 2021 ([Routekaart-Windenergie-op-Zee.png (1292×1688) (rvo.nl)](Routekaart-Windenergie-op-Zee.png) (left) compared to the one from November 2022 (right).

3. Wind farms in 2019

For the year 2019, the wind farms operational on 1-1-2019 are included in HarmCY43-WFP (not only the wind farms operational on the North Sea, but also the ones operational on the onshore part of the domain). Figure 4a gives an overview of those wind farms and figure 4b zooms in on the southern North Sea. As described in section 2.2, the information for the offshore wind farms (red in figure 4a and 4b) comes from EMODNet and open street map, the information for the Dutch onshore wind turbines (blue in figure 4a and 4b) from WindStats and the onshore wind turbines for the rest of the domain (green in figure 4a and 4b) from The Wind Power. Appendix B provides an overview of the offshore wind farms that were operational on 1-1- 2019 (including turbine specifications). The shape file that is used can be found on the WINS50 website (https://wins50.nl/downloads/wins50_windfarm_scenarios.zip).

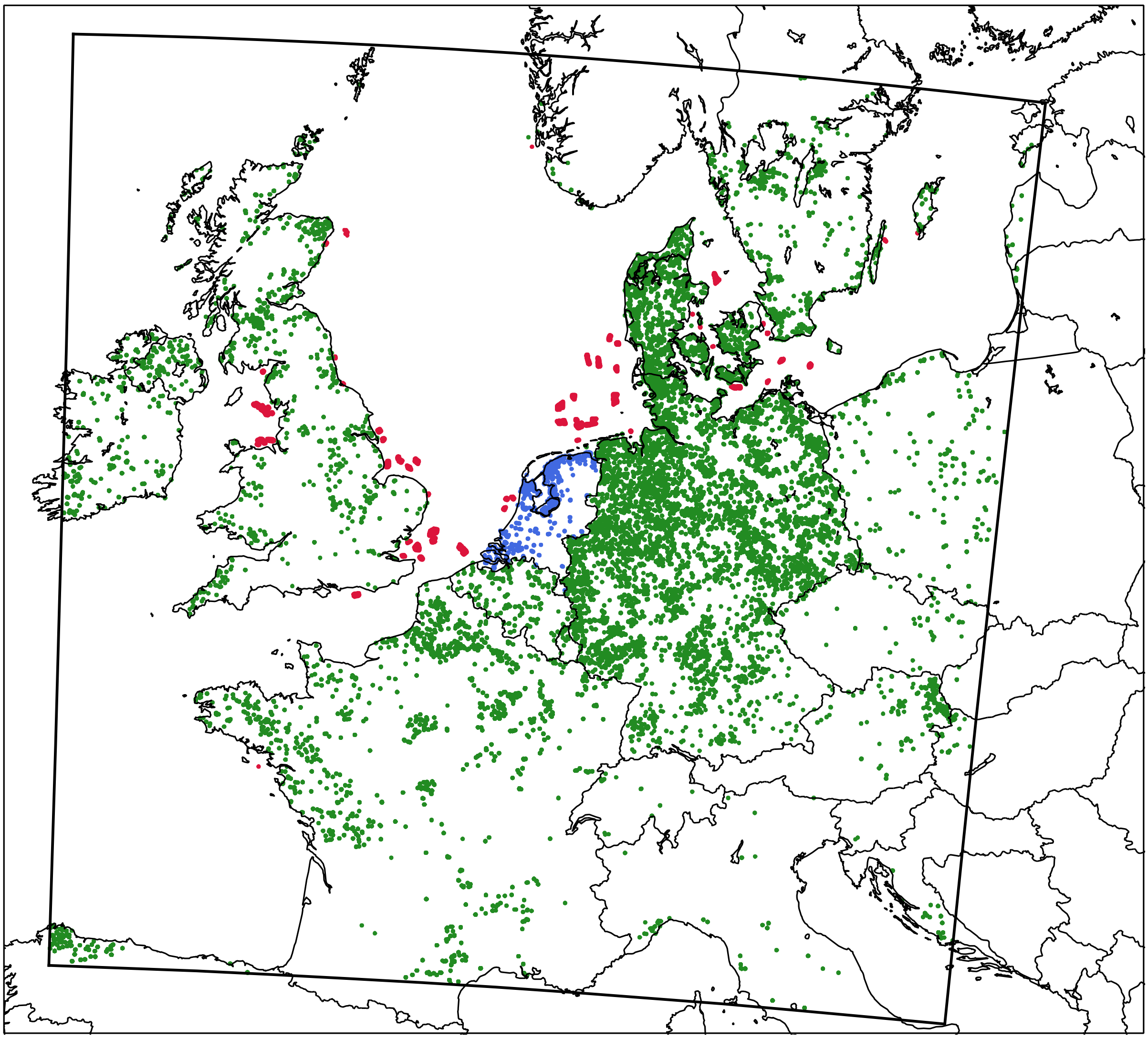

Figure 4a: Wind turbines included in the HARMONIE domain. The location of the turbines in the offshore wind farms (red) are derived from combining EMODNet (shapefiles with outline of wind farms) and open street map data (location of individual turbines). The blue turbine locations in the Netherlands are purchased from WindStats and the green turbine locations in the rest of the domain from The Wind Power.

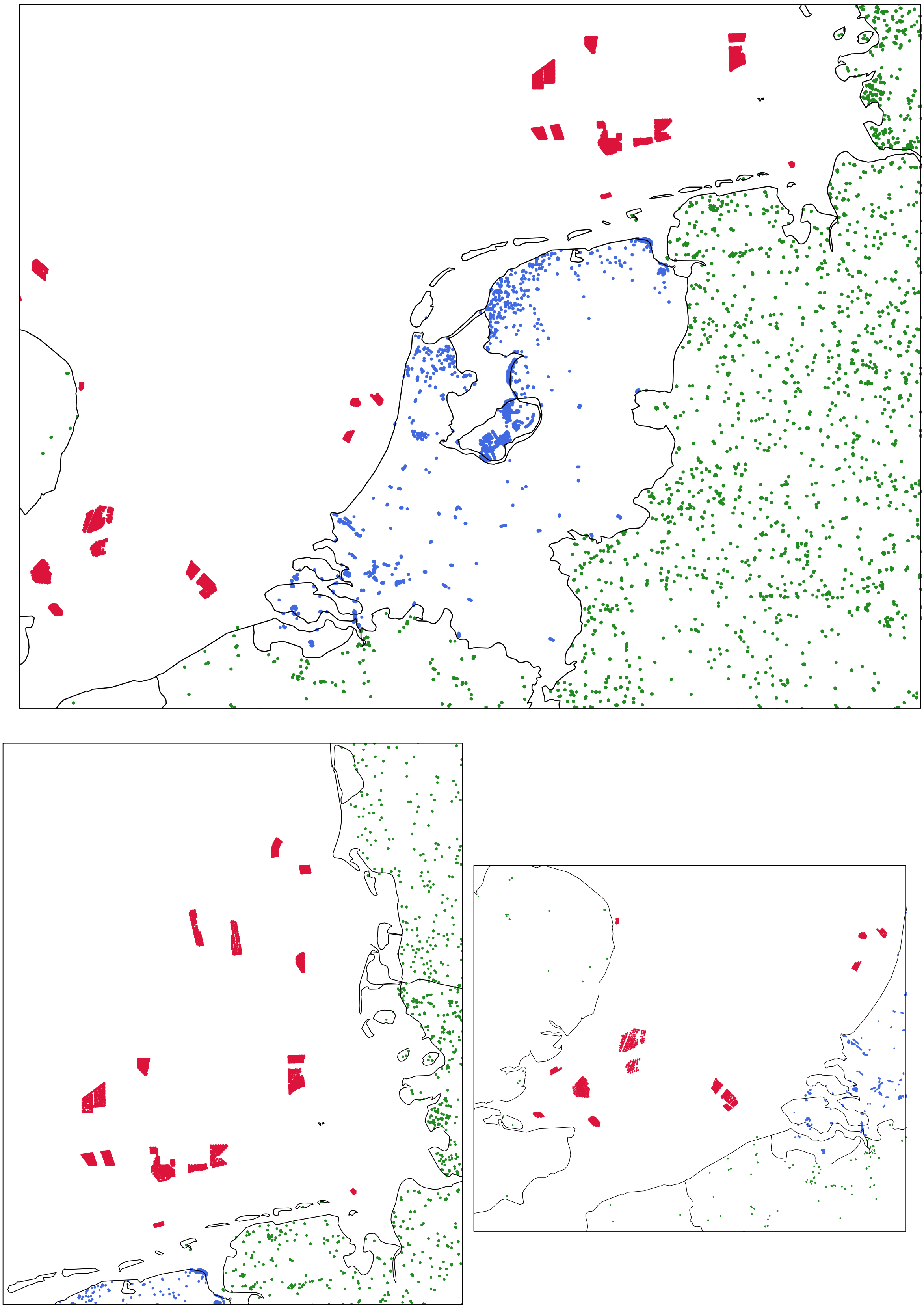

Figure 4b: figure 4a zoomed in on the southern North Sea and the German Bight..

4. Wind farms in 2020

For the year 2020, the offshore wind farms that were built between 1-1-2019 and 1-1-2020 are added. Figure 5a gives an overview of the wind farms added in HarmCy43-WFP in 2020 compared to 2019 (figure 5b zoomed in on the southern North Sea). Appendix B provides an overview of the offshore wind farms that have become operational between 1-1-2020 and 1-1-2021 (including turbine specifications). The shape file that is used can be found on the WINS50 website (https://wins50.nl/downloads/wins50_windfarm_scenarios.zip).

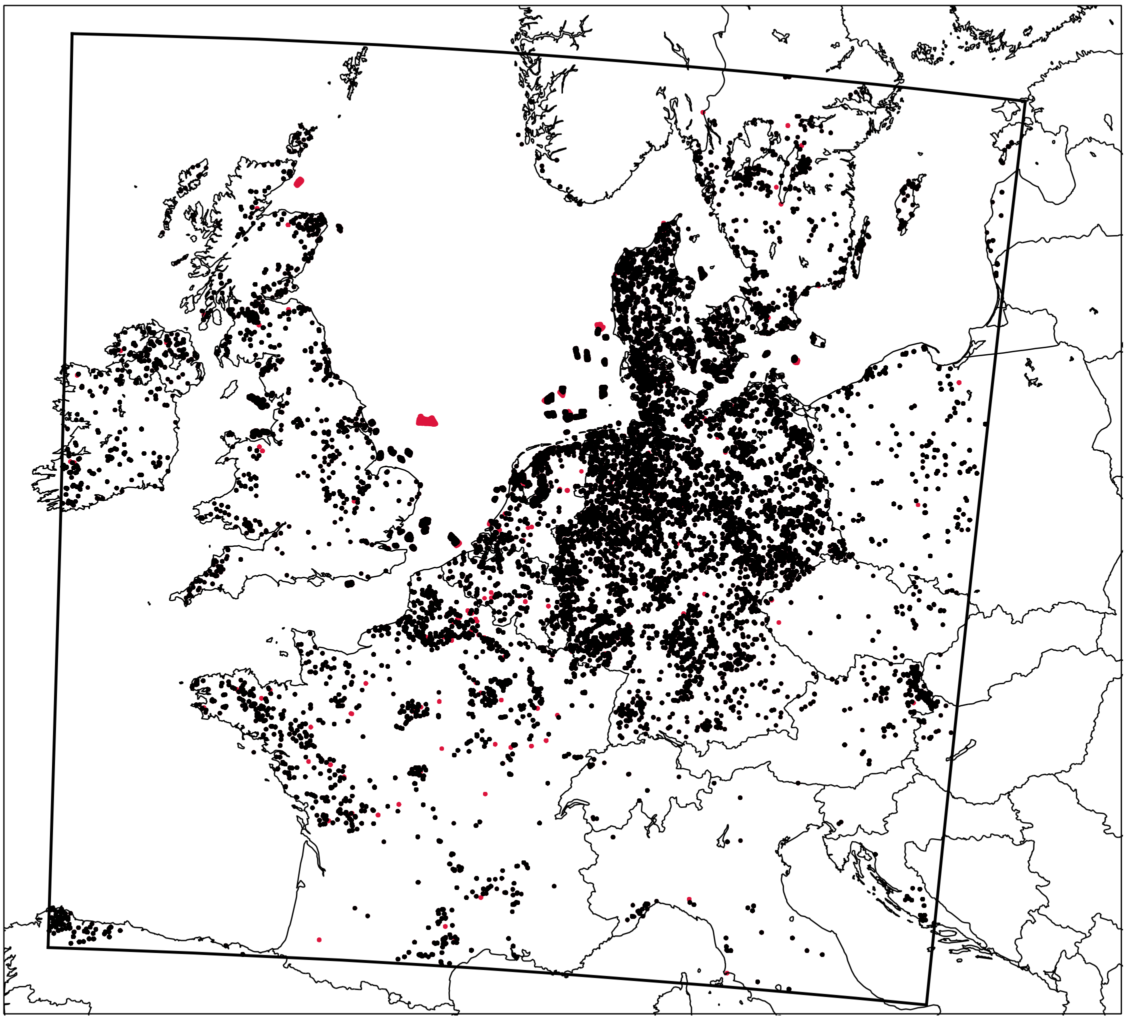

Figure 5a: Wind turbines included in the 2020 simulation, black 2019 data and red newly added offshore and onshore turbines in the 2020 simulation

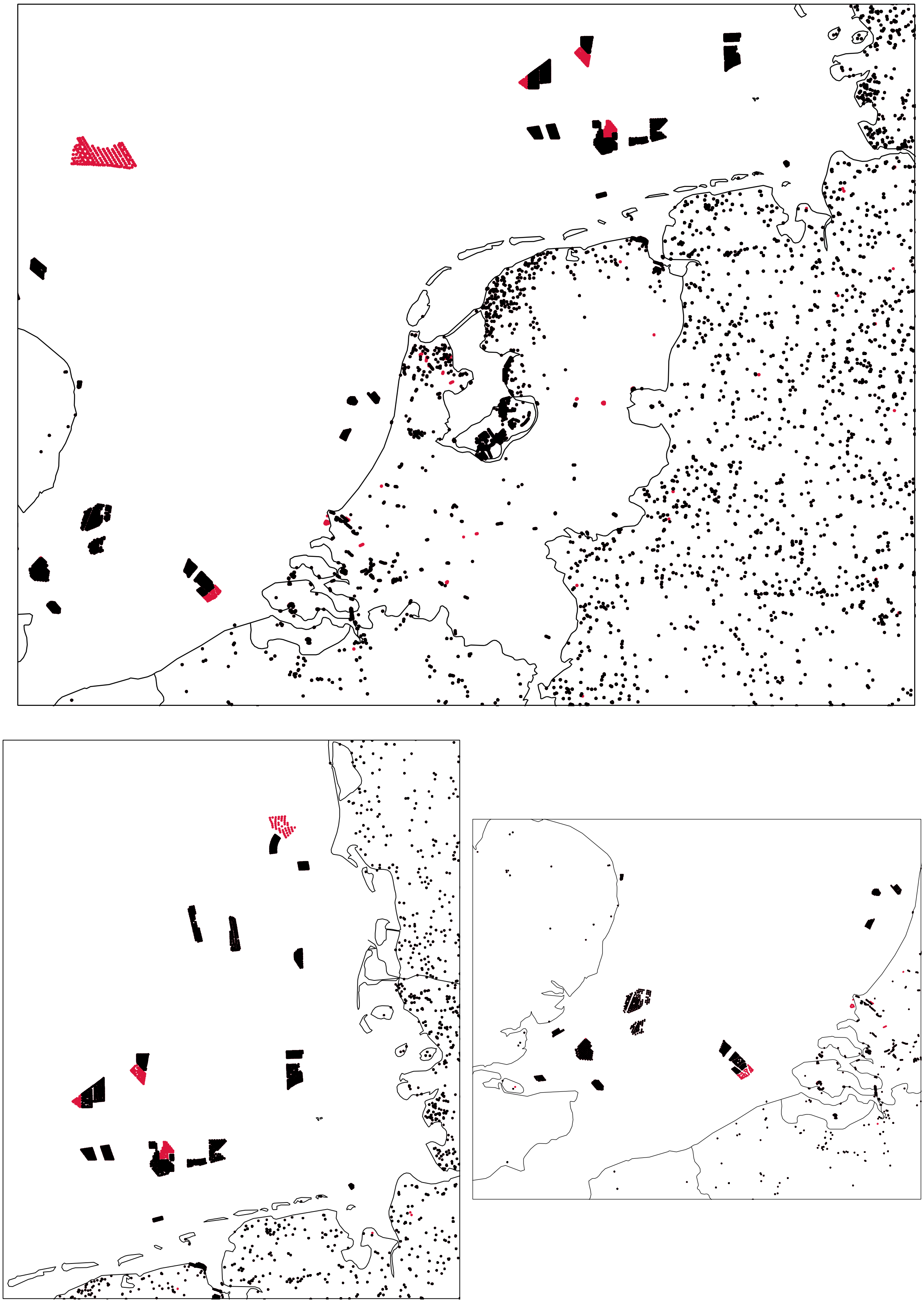

Figure 5b: figure 5a zoomed in on the southern North Sea and the German Bight..

5. Wind farms in 2021

For the year 2021, the offshore wind farms that were built between 1-1-2020 and 1-1-2021 are added. Figure 6a gives an overview of the wind farms added in HarmCy43-WFP in 2021 compared to 2020 (figure 6b zoomed in on the southern North Sea). Appendix B provides an overview of the offshore wind farms that have become operational between 1-1-2021 and 1-1-2022 (including turbine specifications). The shape file that is used can be found on the WINS50 website (https://wins50.nl/downloads/wins50_windfarm_scenarios.zip).

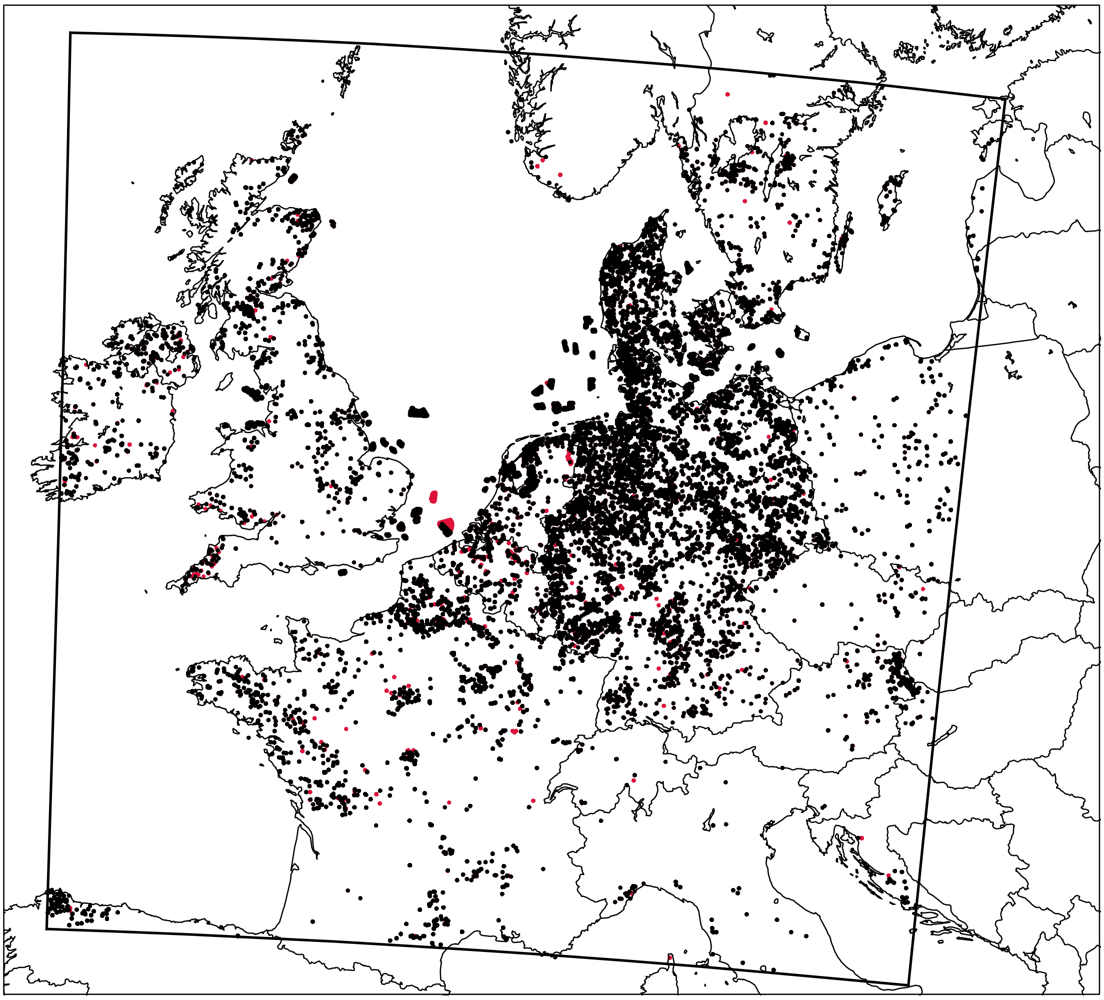

Figure 6a: Wind turbines included in the 2021 simulation, black 2019 and 2020 data combined and red newly added onshore and offshore turbines in the 2021 simulation

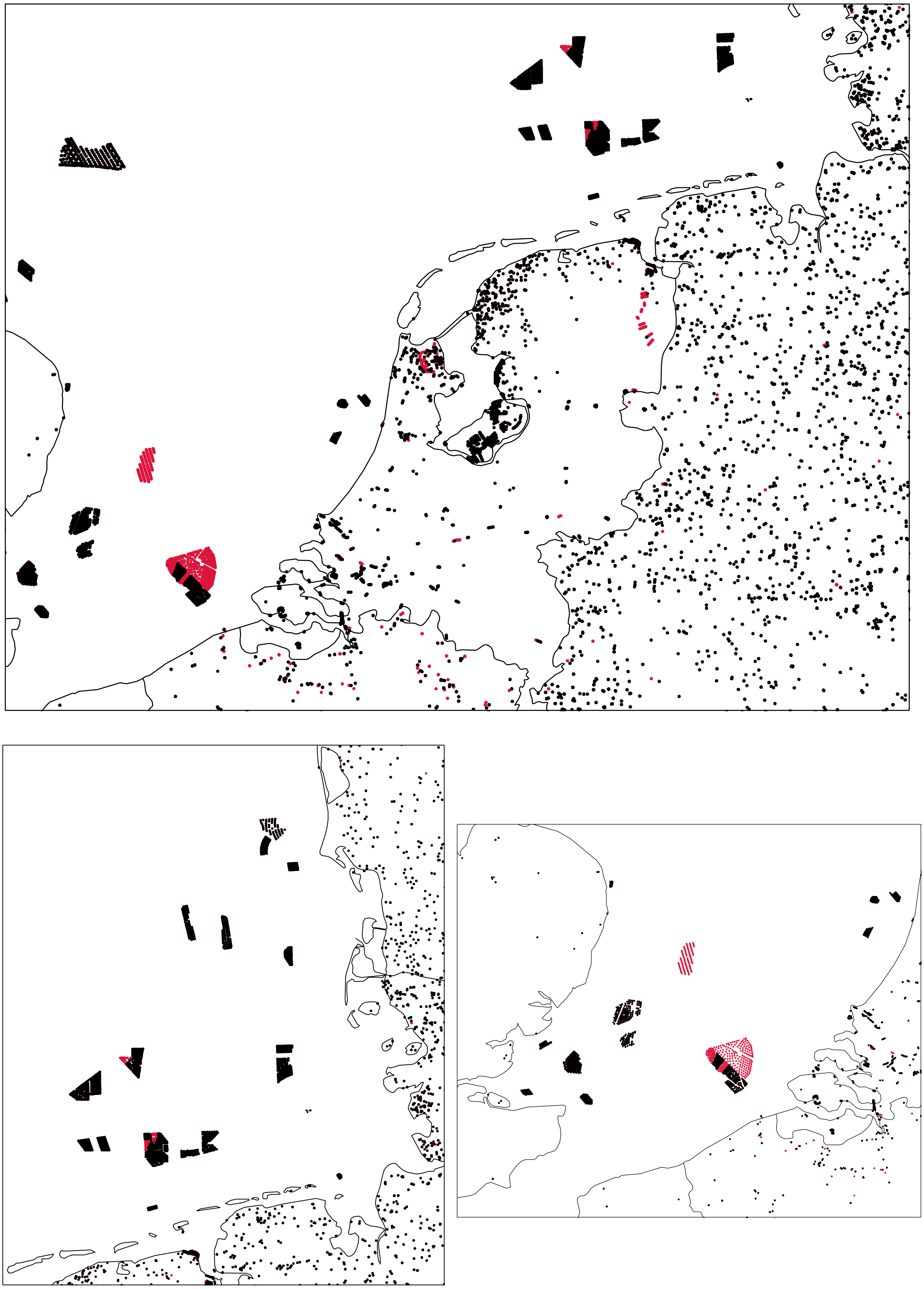

Figure 6b: figure 6a zoomed in on the southern North Sea and the German Bight.

6. WINS50 wind farm scenario for 2050

The WINS50-project provides two meteorological data sets for 2020: one including the operational wind farms on 1-1-2020 (section 4) and one including wind farms based on a hypothetical wind farm scenario for 2050 which we refer to as the 'WINS50-2050 scenario'. This scenario is based on the hypothetical 'WOZEP-2050 scenario' and described in section 2.2.3.

Cumulative offshore wind power **North Sea**	**2019** [MW] (grid connected end 2019)	**2020** [MW]	**2021** [MW]	**2030** [GW]	**2040** [GW]	**2050** [GW]	**2050** [GW] Hypothetical scenario for North Sea (used in WINS50-2050)
Belgium	1556	2262	2262	4.4 - 5.8	4.4 - 5.8?	4.4 - 5.8?	5.320
Denmark[20]	775	775	775	4.8	17.7	17.6	25.156
Germany[21]	6440	6698	6698	27	52	67	29.484
The Netherlands	957	2440.5	2459.5	11.5-21[22]	38	38-72	53.270
Norway (all floating)	2.3	2.3	2.3	1.59	4.59-9.09?	4.59-9.09?	29.588
UK[23]	4726	6658	7608	17 - 40?	40?	40?	45.752
TOTAL North Sea[24]	14456.3	18835.8	19804.8	65.7-100.7	156.7-162.6	171.6-211.5	189.725 (incl France 1.155)

Dutch offshore wind farms operational in 2019, 2020 and 2021 and future plans:

- Operational[25] in 2019: **957 MW** (OWEZ from 2007 108 MW, Prinses Amalia from 2008 120MW, Luchterduinen from 2015 129MW and Gemini from 2016 600 MW)
- Operational in 2020: **2440.5 MW** (Wind farms listed in 2019 plus Borssele I/II 752MW and Borssele III/IV 731.5 MW)
- Operational in 2021: **2459.5 MW**
- 2030: **11.5 GW** (Klimaatakkoord/regeerakkoord Rutte III 49% CO_2-reductie in 2030)
- 2030⁺: **21,5 GW**[26] (plusvariant Klimaatakkoord 55% CO_2-reductie in 2030)
- 2040: **26,5 or 41,5 GW** (based on 11.5 GW in 2030 and a yearly growth of 1.5-3GW[27])
- 2050: **38 or 72 GW** (also based on based on 11.5 GW in 2030 and a yearly growth of 1.5-3GW)

Table 2: National plans for installed capacity for the North Sea and hypothetical WINS50-2050 scenario (a question mark indicates "no plans available, no change anticipated"). National plans change regularly.

There have been significant changes to the North Sea offshore wind energy ambitions since 2020 when the 'WOZEP-2050 scenario' scenario was established. These ambitions will continue to change. Table 2 gives a summary of the national ambitions in 2022. With the current plans , **the total installed offshore wind energy capacity for the whole North Sea** will be between 171.6 and 211.5 GW in 2050. The total installed capacity in the WINS50-2050 scenario is 189.725 GW which is nicely

[20] 2019-2021 from Akhtar et al.: Accelerating deployment of offshore wind energy alter wind climate and reduce future power generation potentials, Nature Sci. Rep., 11, 11826, 2021. Future plans estimated from ens.dk and Juan et al: The value of sector coupling for the development of offshore power grids, 2021, https://www.essoar.org/doi/10.1002/essoar.10509415.1
[21] Total offshore plans Germany: 30 GW (2030), 40 GW (2035) and 70 GW (2045), including Baltic Sea.
[22] https://www.rvo.nl/onderwerpen/windenergie-op-zee/routekaart
[23] Total ambition UK 2030 40GW, but that is not only North Sea. It includes 25 GW floating (Scotland). No official plans for after 2030.
[24] For Sweden (all in Baltic) 190 MW (2019), 21175 MW (2021), 4 GW (2030), 10 GW (2040), and 17 GW (2050).
[25] https://en.wikipedia.org/wiki/List_of_offshore_wind_farms_in_the_North_Sea
[26] Verkenning aanlanding wind op zee (VAWOZ) | RVO.nl | Rijksdienst
[27] Wind op zee na 2030 - Wind op zee

within this range. However, on a country level we already see significant discrepancies: WINS50-2050 is not ambitious enough for Germany and too ambitious for Norway. **The total installed offshore wind energy capacity for the Netherlands** is about 53GW, which is close to the most ambitious "Samen Duurzaam" scenario of 60GW presented by PBL in 2018[28].

Figure 7 shows the areas that are designated for Dutch wind energy in "Programma Noordzee 2022-2027". These areas are not supposed to be completely filled with wind turbines, but future wind farms are supposed to be built within these areas. Note that not all wind farms in the WINS50-2050 scenario are within the areas currently designated for wind energy. This is because the WINS50-2050 scenario is based on the WOZEP-2050 scenario from 2020 and plans for offshore wind energy keep changing. Because the future remains uncertain, we decided to stick to the WOZEP-2050 scenario (as good a guess as any) unless there was a good reason for adjustments (Appendix A).

Figure 7: areas designated for Dutch wind energy are the yellow hatched areas ("Programma Noordzee 2022-2027"[29]).

[28] Matthijsen, J. et al. (2018), De toekomst van de Noordzee. De Noordzee in 2030 en 2050: een scenariostudie, Den Haag: PBL. (https://www.pbl.nl/sites/default/files/downloads/pbl-2018-toekomst-van-de-noordzee-2728.pdf)
[29] https://www.noordzeeloket.nl/beleid/programma-noordzee-2022-2027/ (section 9.4 of the report)

Figure 8a, 8b and 8c show the WINS50-2050 scenario, where 8a is zoomed in on the southern North Sea, 8b on the Frisian Isles and the German Bight and 8c on the Dutch part of the North Sea.

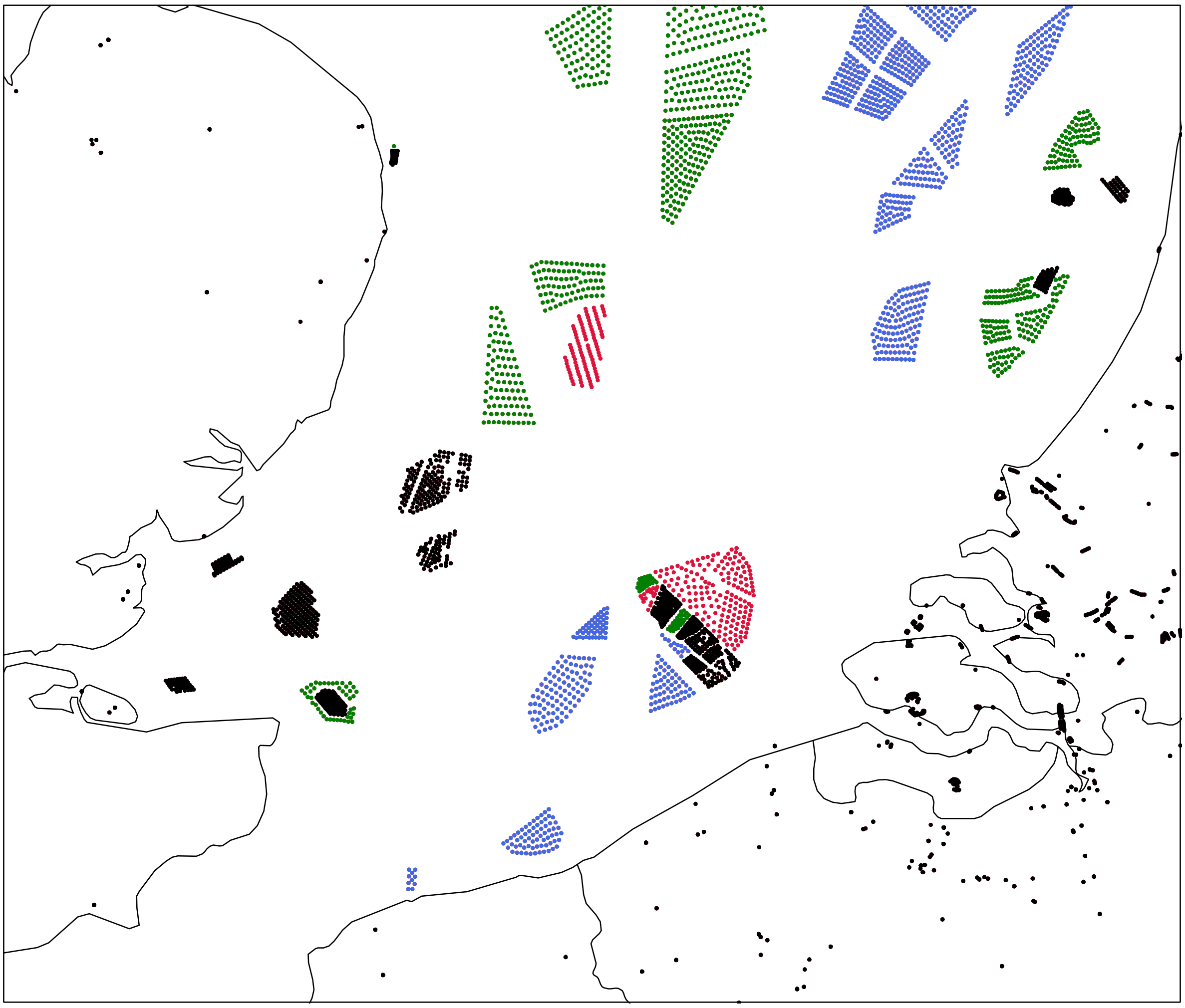

Figure 8a: hypothetical wind farm scenario 2050 in WINS50 study (WINS50-2050 scenario). In black wind farms 1-1-2020, red wind farms built between January 2020 and April 2021, in blue (15MW) and green (10MW) planned wind farms. As figure 2, but zoomed in on southern North Sea.

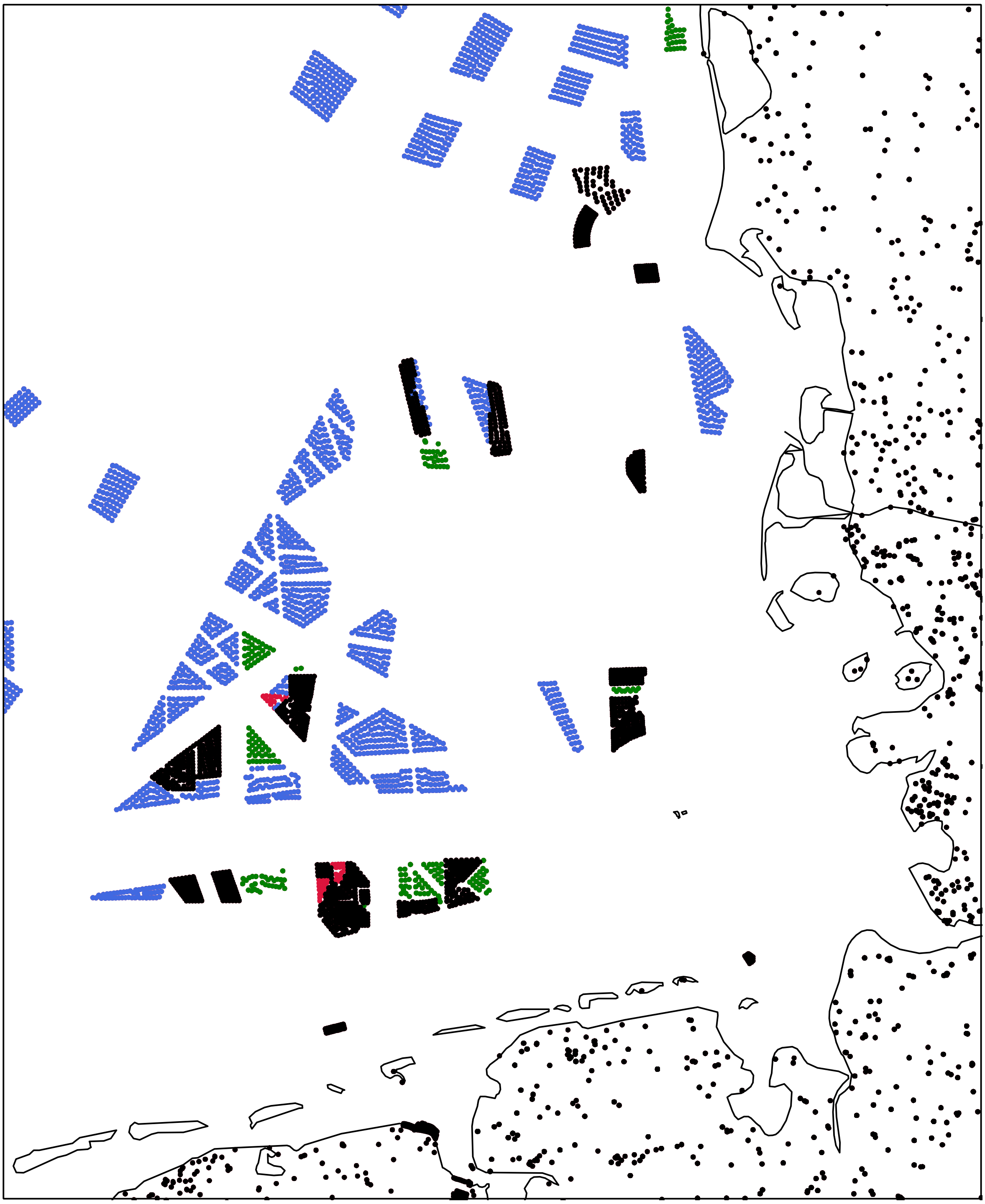

Figure 8b: hypothetical wind farm scenario 2050 in WINS50 study (WINS50-2050 scenario). In black wind farms 1-1-2020, red wind farms built between January 2020 and April 2021, in blue (15MW) and green (10MW) planned wind farms. As figure 2, but zoomed in on Frisian Isles and the German Bight.

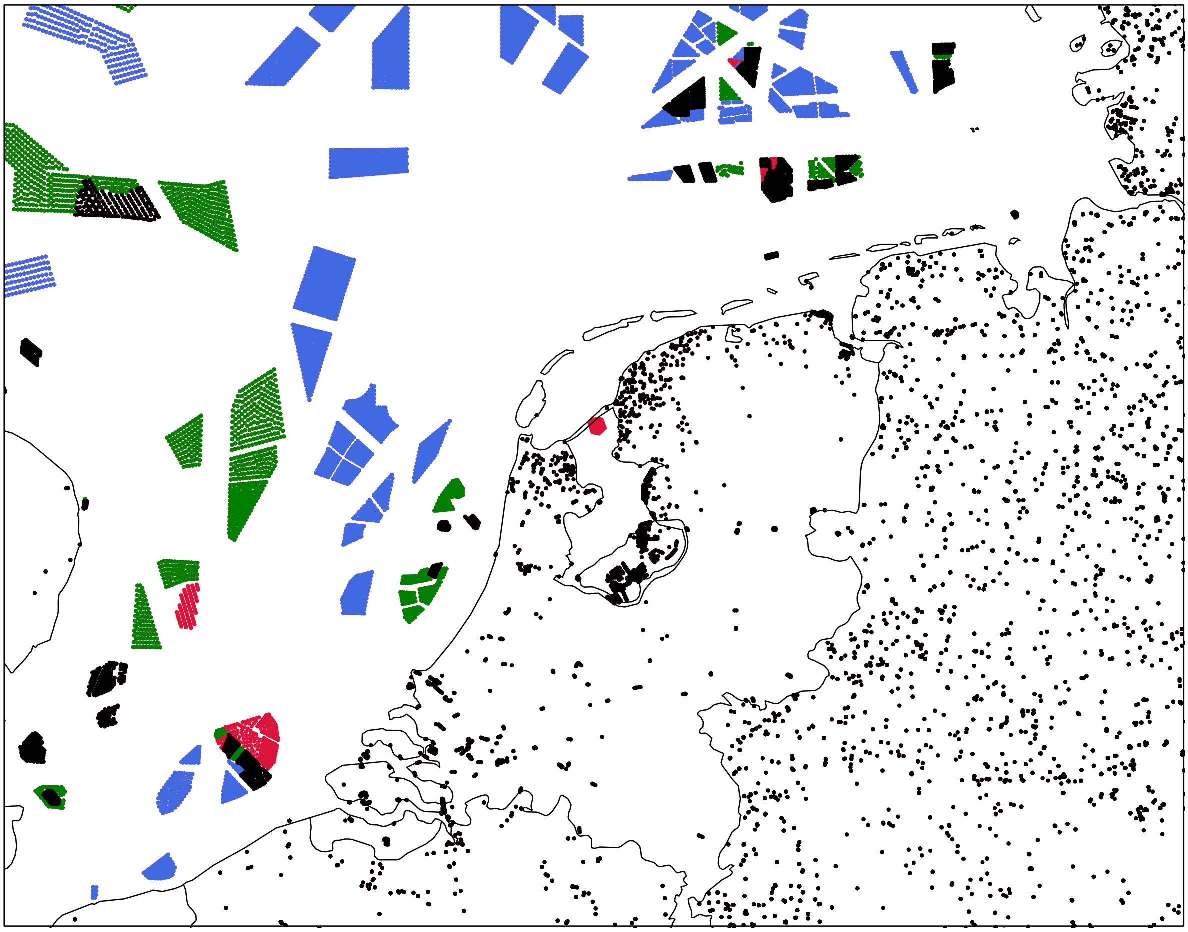

Figure 8c: hypothetical wind farm scenario 2050 in WINS50 study (WINS50-2050 scenario). In black wind farms 1-1-2020, red wind farms built between January 2020 and April 2021, in blue (15MW) and green (10MW) planned wind farms. As figure 2, but zoomed in on Dutch part of the North Sea.

Probably many of the presently operational wind farms will be decommissioned by the year 2050, but we choose to keep them to facilitate a comparison with the simulation with present capacity.

The shape file that is used can be found on the WINS50 website (https://wins50.nl/downloads/wins50_windfarm_scenarios.zip).

Appendix A: Differences between the WOZEP-2050 and WINS50-2050 scenario

Dutch offshore wind farms:

- Wind Farm Zone (WFZ) **North Hinder** (figure A1): is part of the Dutch offshore wind energy plans in 2018 ("Routekaart 2018") and the WOZEP-2050 scenario, but not included in WINS50-2050 scenario because it was cancelled (too small to produce the planned 400MW[30] and too expensive to be used as a test site).
- WFZ **IJmuiden Ver**: plans for northward expansion of the Ijmuiden Ver wind farm zone[31] [32] include two additional "kavels" (V and VI in figure A1) north of the four 1 GW "kavels" (I, II, II and IV in figure A2. In the WINS50-2050 scenario we filled the whole northern part of Ijmuiden-Ver (not only the two additional "kavels") with 8 MW/km^2 of 15MW turbines. So in total 318 km^2 * 8 MW/km^2 = 2.5 GW, which is a bit different from the government plans (2 GW in total). Coordinates of the "kavels" are obtained from the RVO site[33].
- WFZ **Hollands Kust West (HKW)**: we implemented three 700 MW "kavels" at Hollandse Kust West (HKW)[34], all 15MW turbines. Two 700MW "kavels" (VI and VII) are already planned, one (VIII), has been considered as an extension, but actual implementation is uncertain. The coordinates of the "kavels" are obtained from the RVO site[35].
- WFZ **Hollandse Kust Zuid (HKZ):** we implemented four planned "kavels" [36] of 760MW, all 10MW turbines. The coordinates of the "kavels" are obtained from the RVO site[37]. HKZ is "an extension, mainly to the south, of offshore wind farm Luchterduinen (LUD).
- WFZ **Ten Noorden van de Wadden (TNW)**: we implemented one "kavel" west of existing wind farm Gemini (700MW) conform the government plans (figure A3). The WOZEP-2050 scenario also included the area between the two Gemini wind farms, but this area is not suitable for wind energy so in the WINS50-2050 we left it out.
- WFZ **Hollandse Kust Noord (HKN)**: there are significant differences with the WOZEP-2050 scenario because WOZEP includes "wind farm zone" and "kavels" and WINS50 only the "kavels" (figure A4). HKN is to the north of Princess Amalia Wind Farm (PAWF).
- WFZ **Borssele**: the only difference with the WOZEP-2050 scenario is that we did not have to assume wind turbine locations evenly spread over Borssele III and IV (figure A5) like in WOZEP-2050 scenario, because the wind farms have been fully operational since the beginning of 2021. The exact locations of the turbines are derived from open street map.

Other offshore wind farms on the North Sea:

- We added three 1.5 GW offshore wind farms in UK waters (Round 4 Area1-3)[38]

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[30] Noord Hinder Offshore Wind Farm - Cancelled - Netherlands | 4C Offshore
[31] 4-ontwerp-programma-noordzee-2022-2027 (3).pdf page 101)
[32] https://www.rvo.nl/sites/default/files/2020/12/VAWOZ-Versnelling-2030-DEF-presentatie%209-10-december.pdf
[33] https://offshorewind.rvo.nl/cms/view/5c06ac88-c12f-4903-89f3-27d66937b7e9/general-information-ijmuiden-ver
[34] Project and Site Description Hollandse Kust (west) Wind Farm Zone (rvo.nl)
[35] https://offshorewind.rvo.nl/generalw
[36] Hollandse Kust (Zuid) Wind Farm Zone, Sites I and II | RVO.nl and Hollandse Kust (zuid) Wind Farm Zone, Sites III and IV | RVO.nl
[37] https://offshorewind.rvo.nl/generalzh
[38] https://www.thecrownestate.co.uk/media/3721/the-crown-estate-offshore-wind-leasing-round-4-selected-projects.pdf : projects 1, 2 and 3 (two 1.5 GW RWE renewables and 1.5 Green investment group Total)

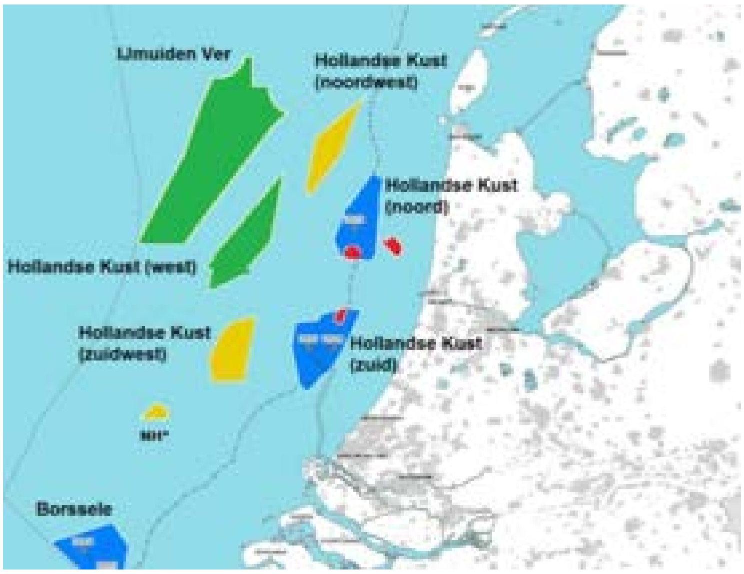

Figure A1: North Hinder (NH in this figure) is in the WOZEP-2050 scenario, but not in WINS50-2050 scenario. The original plan for North Hinder was 400MW (with 8MW/km² this area can produce 240 MW).*

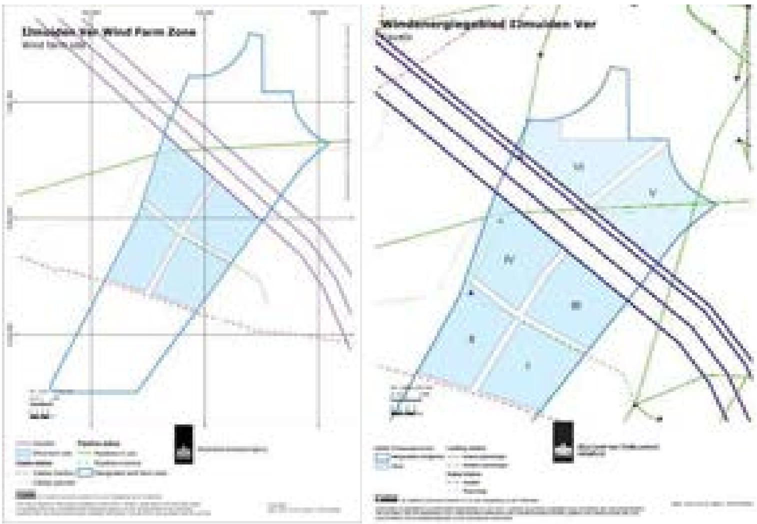

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Figure A2: Base Map Ijmuiden-Ver[39] left) and planned expansion north of the shipping lanes ("kavels" V and VI, each 1 MW[40]).

[39] https://offshorewind.rvo.nl/generalIJmuiden

[40] 4-ontwerp-programma-noordzee-2022-2027 (3).pdf page 101)

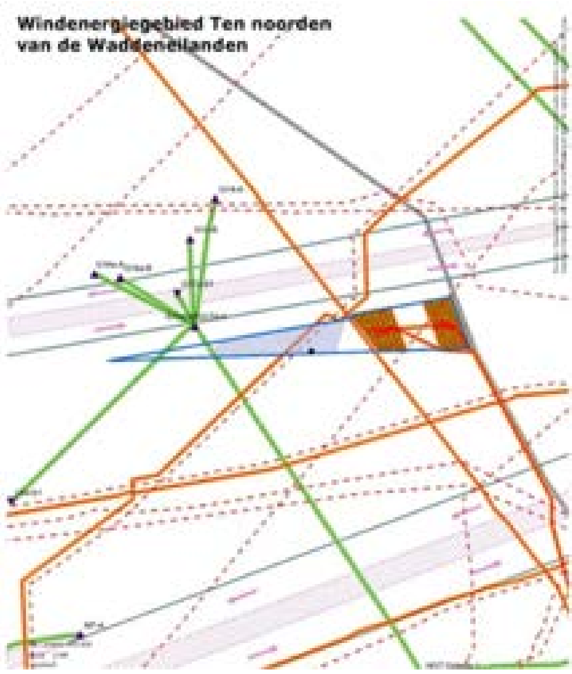

Figure A3: "Ten Noorden van de Waddeneilanden" (TNW): government plans for TNW[41] where the two Gemini wind farms are shown in orange/brown and the suggested new "kavel" that is included in the WINS50-2050 scenario in light blue.

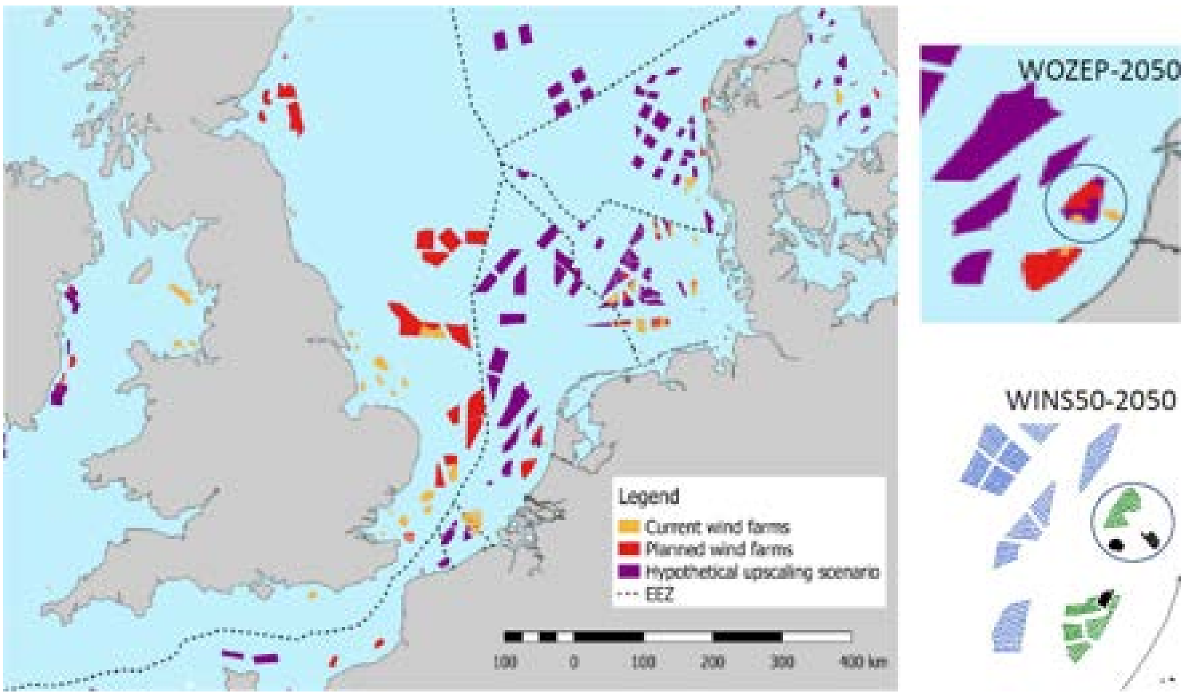

Figure A4 HKN: left and right above WOZEP-2050 scenario, below WINS50-2050. WOZEP-2050 includes "wind farm zones" (purple) and "kavels" (red; operational). In WINS50-2050 only the "kavels" (red) are included, not the "wind farm zones" (purple).

[41] https://www.rvo.nl/sites/default/files/2021/01/Concept-notitie-reikwijdte-en-detailniveau-windenergiegebied-Ten-noorden-van-de-Waddeneilanden-D.pdf (fig 3.1).

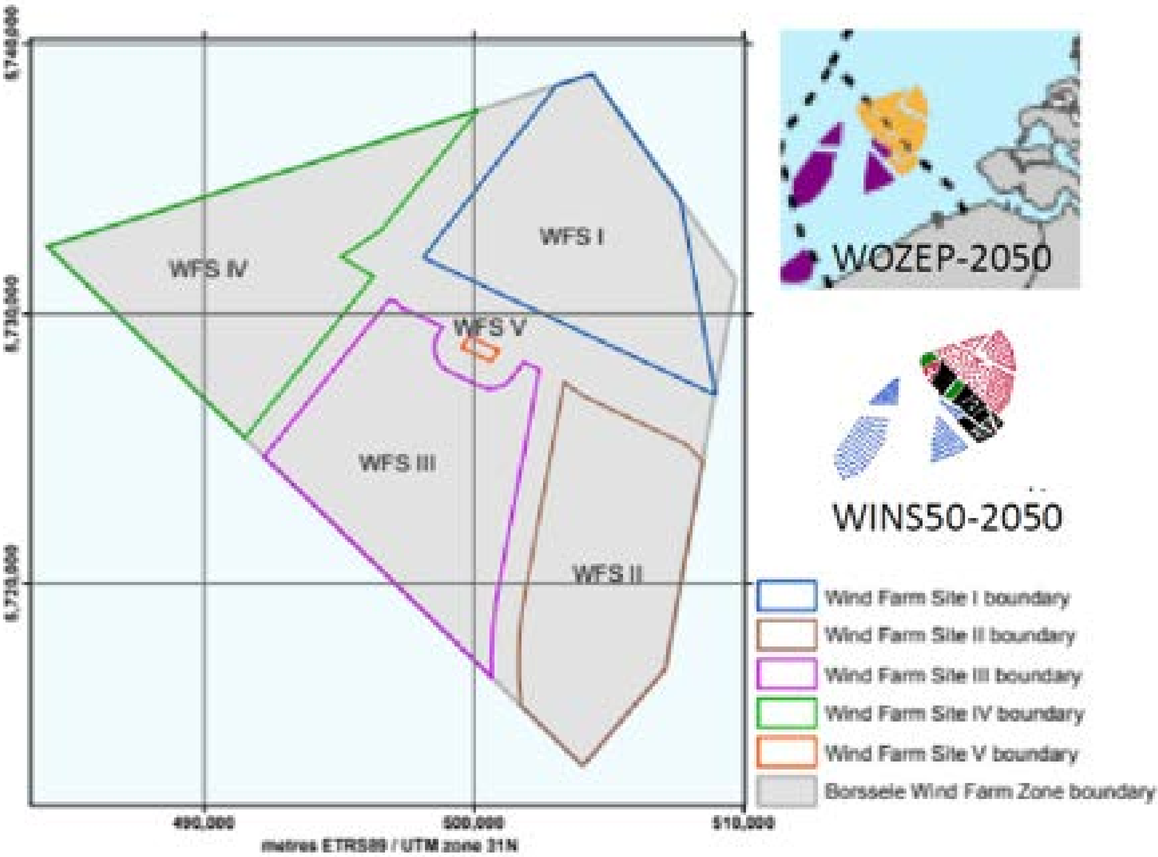

Figure A5 Borssele: left according to project and site description[42], right top according to WOZEP-2050 scenario and right below according to WINS50-2050 scenario

[42] Figure 3 from [1469778189psd borssele windfarm iii+iv web.pdf (rvo.nl)]

Appendix B: Overview of the offshore wind farms that were operational in 2019, 2020 and 2021 and included in the HarmCy43-WFP simulations

Offshore wind farms operational on 1-1-2019								
Name	Country	Lat	Lon	Source	Turbine type	Number of turbines	Turbine power (MW)	Wind farm power (MW)
Aberdeen	UK	57,22	-1,99	EMOD	REF-8.0	11	8	88
Alpha Ventus	DE	54,01	6,61	OSM	Senvion-5	12	5	60
Amalia	NL	52,59	4,23	OSM	V80_ECN	60	2	120
Amrumbank West	DE	54,52	7,74	OSM	SWT-3.6-120	80	3,6	288
Anholt	DK	56,62	11,22	OSM	SWT-3.6-120	111	3,6	399,6
BARD Offshore	DE	54,35	5,99	OSM	Senvion-5	80	5	400
Barrow	UK	53,99	-3,29	OSM	V90_ECN	30	3	90
Belwind	BE	51,68	2,82	OSM	V90-3.0	55	3	165
Blyth Dem.Park	UK	55,14	-1,41	OSM	V164-8.0	5	8	40
Borkum Riffgrund I	DE	53,96	6,56	OSM	SWT-4.0-120	78	4	312
Borkum Riffgrund II (E)	DE	53,98	6,61	EMOD	REF-8.0	5	8	40
Borkum Riffgrund II (W)	DE	53,96	6,48	EMOD	REF-8.0	51	8	408
Burbo Bank	UK	53,49	-3,19	OSM	SWT-3.6-107	25	3,6	90
Burbo Bank Ext.	UK	53,48	-3,24	OSM	V164-8.0	32	8	256
Butendiek	DE	55,01	7,77	OSM	SWT-3.6-120	80	3,6	288
DanTysk	DE	55,15	7,19	OSM	SWT-3.6-120	80	3,6	288
Dudgeon	UK	53,27	1,38	OSM	REF-6.0	67	6	402
Dummy	UK	52,67	1,79	EMOD	DTU10	1	10	10
EnBW Baltic 1	DE	54,61	12,66	OSM	SWT-2.3-93	21	2,3	48,3
EnBW Baltic 2	DE	54,98	13,16	OSM	SWT-3.6-120	80	3,6	288
Galloper (N)	UK	51,98	1,99	OSM	REF-6.0	38	6	228
Galloper (S)	UK	51,78	2,01	OSM	REF-6.0	18	6	108
Gemini (E)	NL	54,03	6,05	OSM	SWT-4.0-130	75	4	300
Gemini (W)	NL	54,04	5,89	OSM	SWT-4.0-130	75	4	300
Global Tech I	DE	54,50	6,37	OSM	Senvion-5	80	5	400
Gode Wind 1	DE	54,02	6,99	OSM	REF-6.0	55	6	330

Gode Wind II	DE	54,07	7,03	OSM	REF-6.0	42	6	252
Greater Gabbard (N)	UK	51,94	1,92	OSM	SWT-3.6-107	102	3,6	367,2
Greater Gabbard (S)	UK	51,76	1,95	OSM	SWT-3.6-107	38	3,6	136,8
Gunfleet Sands I	UK	51,73	1,22	OSM	SWT-3.6-107	30	3,6	108
Gunfleet Sands II	UK	51,73	1,25	OSM	SWT-3.6-107	18	3,6	64,8
Gunfleets Sands (Dem.Proj.)	UK	51,71	1,20	OSM	REF-6.0	2	6	12
Gwynt y Mor (E)	UK	53,46	-3,53	OSM	SWT-3.6-107	71	3,6	255,6
Gwynt y Mor (W)	UK	53,45	-3,64	OSM	SWT-3.6-107	89	3,6	320,4
Horns Rev 1	DK	55,49	7,86	OSM	SWT-3.6-120	30	3,6	108
Horns Rev 2	DK	55,61	7,59	OSM	SWT-2.3-93	91	2,3	209,3
Humber Gateway	UK	53,62	0,28	OSM	V112_ECN	73	3	219
Hywind	UK	57,49	-1,35	EMOD	REF-6.0	5	6	30
Inner Dowsing	UK	53,20	0,45	OSM	SWT-3.6-107	27	3,6	97,2
Kentish Flats	UK	51,46	1,10	OSM	V90_ECN	30	3	90
Kentish Flats (ext)	UK	51,45	1,09	OSM	V112-3.3	15	3,3	49,5
Lincs (E)	UK	53,16	0,48	OSM	SWT-3.6-120	72	3,6	259,2
Lincs (W)	UK	53,21	0,46	OSM	SWT-3.6-120	3	3,6	10,8
London Array	UK	51,62	1,50	OSM	SWT-3.6-120	175	3,6	630
Luchterduinen	NL	52,41	4,17	OSM	V112_ECN	43	3	129
Lynn	UK	53,14	0,47	OSM	SWT-3.6-107	27	3,6	97,2
Meerwind Sud/Ost	DE	54,38	7,70	OSM	SWT-3.6-120	80	3,6	288
Methil Dem. Project	UK	56,17	-3,02	OSM	REF-6.0	1	6	6
Nobelwind (east)	BE	51,66	2,82	OSM	V112-3.3	40	3,3	132
Nobelwind (west)	BE	51,68	2,79	OSM	V112-3.3	10	3,3	33
Nordergruende	DE	53,83	8,17	OSM	Senvion-6.2	18	6,15	110,7
Nordsee One	DE	53,98	6,83	OSM	Senvion-6.2	54	6,15	332,1
Nordsee Ost	DE	54,45	7,69	OSM	Senvion-6.2	48	6,15	295,2
North Hoyle	UK	53,42	-3,44	OSM	V80_ECN	30	2	60
Northwind	BE	51,61	2,90	OSM	V112_ECN	73	3	216
Nysted	DK	54,55	11,71	OSM	SWT-2.3-82	72	2,3	165,6
Ormonde	UK	54,09	-3,43	OSM	Senvion-5	30	5	150

OWEZ	NL	52,62	4,41	OSM	V90_ECN	36	3	108
Race Bank	UK	53,29	0,82	OSM	REF-6.0	91	6	546
Rampion	UK	50,66	-0,26	OSM	V112-3.45	116	3,45	400,2
Rentel	BE	51,59	2,93	OSM	REF-6.0	42	6	252
Rhyl Flats	UK	53,38	-3,65	OSM	SWT-3.6-107	25	3,6	90
Riffgat	DE	53,69	6,47	OSM	SWT-3.6-120	30	3,6	108
Robin Rigg (E)	UK	54,76	-3,69	OSM	V90_ECN	28	3	84
Robin Rigg (W)	UK	54,75	-3,72	OSM	V90_ECN	30	3	90
Rodsand 2	DK	54,56	11,54	OSM	SWT-2.3-93	90	2,3	207
Sand Bank (N)	DE	55,25	6,84	OSM	SWT-4.0-130	31	4	124
Sandbank (S)	DE	55,17	6,87	OSM	SWT-4.0-130	41	4	164
Scroby Sands	UK	52,65	1,78	OSM	V80_ECN	30	2	60
Sheringham Shoal	UK	53,14	1,15	OSM	SWT-3.6-107	88	3,6	316,8
Teesside	UK	54,64	-1,09	EMOD	SWT-2.3-93	27	2,3	62,1
Thanet	UK	51,43	1,64	OSM	V90_ECN	100	3	300
Thornton Bank I	BE	51,54	2,92	OSM	Multiple	30	5,96	178,8
Thornton Bank II	BE	51,57	2,99	OSM	Senvion-6.2	24	6,15	147,6
Trianel Borkum I	DE	54,05	6,46	OSM	Senvion-5	40	5	200
Veja Mate	DE	54,33	5,88	OSM	REF-6.0	67	6	402
Walney 1	UK	54,04	-3,50	OSM	SWT-3.6-107	51	3,6	183,6
Walney 2	UK	54,07	-3,60	OSM	SWT-3.6-107	51	3,6	183,6
Walney Extension (WOW03)	UK	54,13	-3,84	OSM	V164-8.0	40	8	320
Walney Extension (WOW04)	UK	54,06	-3,63	OSM	REF-6.0	47	6	282
West of Duddon Sands	UK	53,99	-3,45	OSM	SWT-3.6-120	108	3,6	388,8
Westermost Rough	UK	53,80	0,16	OSM	REF-6.0	35	6	210
Wikinger	DE	54,84	14,06	OSM	Senvion-5	70	5	350

Offshore wind farms (and turbine types) that have become operational between 1-1-2019 and 1-1-2020

Name	Country	Lat	Lon	Source	Turbine type	Number of turbines	Turbine power (MW)	Wind farm power (MW)
Arkona	DE	54,78	14,12	OSM	REF-6.0	60	6	360
Beatrice	UK	58,24	-2,85	OSM	REF-6.0	84	6	504
Deutsche Bucht	DE	54,30	5,79	OSM	V164-8.0	31	8	248

Hohe See	DE	54,46	6,32	OSM	REF-6.0	71	6	426
Horns Rev 3	DK	55,70	7,67	OSM	V164-8.0	49	8	392
Hornsea 1	UK	53,91	1,92	OSM	REF-6.0	174	6	1044
Merkur	DE	54,05	6,56	OSM	Haliade-6	66	6	396
Norther	BE	51,54	3,01	OSM	V164-8.0	44	8,4	359,6

Offshore wind farms (and turbine types) that have become operational between 1-1-2020 and 1-1-2021

Name	Country	Lat	Lon	Source	Turbine type	Number of turbines	Turbine power (MW)	Wind farm power (MW)
Albatros	DE	54,49	6,24	OSM	REF-6.0	16	6	96
Borssele 1	NL	51,74	3,05	OSM	REF-8.0	45	8	360
Borssele 2	NL	51,65	3,05	OSM	REF-8.0	47	8	376
Borssele 3	NL	51,70	2,99	OSM	V164-8.0	37	8	396
Borssele 4	NL	51,74	2,89	OSM	V164-8.0	40	8	320
East Anglia ONE	UK	52,26	2,49	OSM	REF-6.0	102	6	612
Northwester 2	BE	51,69	2,76	OSM	V164-8.0	23	8,4	193,2
Seamade (Mermaid)	BE	51,72	2,76	EMOD	REF-8.0	30	8	240
Seamade (Seastar)	BE	51,63	2,86	EMOD	REF-8.0	30	8	240
Trianel Borkum 2 (E)	DE	54,07	6,49	OSM	Senvion-6.2	16	6,15	98,4
Trianel Borkum 2 (W)	DE	54,04	6,44	OSM	Senvion-6.2	16	6,15	98,4