Baltic LINes

Coherent Linear Infrastructures
in Baltic Maritime Spatial Plans

CAPACITY DENSITIES OF EUROPEAN OFFSHORE WIND FARMS

Report conducted by Deutsche WindGuard GmbH

Interreg
Baltic Sea Region

EUROPEAN UNION
EUROPEAN REGIONAL DEVELOPMENT FUND

Foreword

The Baltic Sea faces an increasing spatial demand for human activities. In particular offshore renewable energy is a quite new interest with a considerably high demand on sea space. In light of climate protection policy some countries have set national energy targets for offshore wind. For the implementtation of these targets the offshore wind energy sector competes with other uses on limited space.

Baltic LINes aims at achieving greater transnational coherence for inter alia energy infrastructure in the Baltic Sea Region in order to ensure efficient and sustainable use of the Baltic Sea space. One of the questions to solve in this context is the extent of sea space that is required to install a certain capacity of offshore wind energy and related decisive factors for this so called capacity density of offshore wind farms.

To address this issue the Federal Maritime and Hydrographic Agency, BSH, has tendered a study dealing with the prospective capacity density of European offshore wind farms. The present study has been conducted by the German consultancy Deutsche WindGuard GmbH.

The study developed under work package 2 “Sector trends and requirements for MSP” concentrates on two key questions:

- What mean capacity density (MW per km²) can be assumed for future offshore wind farms?
- How do different national regulatory frameworks influence capacity density?

This report covers the following sections:

Theory analysis and literature review	• theoretical background, definitions • Review and evaluation of existing assumptions • influencing factors, expected developments
National planning approaches and standards	• Focus on planning level • Analysis of different national planning approaches in the North and Baltic Sea
Analysis of realized offshore wind farms	• Focus on implementation level • Analysis of capacity densities of existing wind farms

The study results serve as input for the report on energy scenarios for the Baltic Sea under work package 2 by analysing future conditions for MSP as well as a relevant input for the planning criteria report under work package 4.2. Please note that the report does not claim to be complete in one or the other way.

Hamburg, June 21st 2018
Annika Koch
Federal Maritime and Hydrographic Agency (BSH)

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Authors: DEUTSCHE WINDGUARD
Rasmus Borrmann
Dr. Knud Rehfeldt
Anna-Kathrin Wallasch
Silke Lüers

Cover photo: Alpha Ventus (source : BSH)
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(Federal Maritime and Hydrographic Agency)
Bernhard-Nocht-Straße 78
20359 Hamburg

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DEUTSCHE WINDGUARD

Deutsche WindGuard GmbH
Oldenburger Straße 65
26316 Varel
Germany

Phone +49 4451 9515 0
Fax +49 4451 9515 29
Email info@windguard.de
URL http://www.windguard.com/

We hereby state, that the results in this report are based upon generally acknowledged and state-of-the-art methods and have been neutrally conducted to the best of our knowledge and belief. No guarantee, however, is given and no responsibility is accepted by Deutsche WindGuard GmbH for the correctness of the derived results.

This report covers 83 pages.

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LIST OF ABBREVIATIONS

AEP	Annual Energy Production
FLH	Full Load Hours
LCOE	Levelized Cost of Electricity
MSP	Maritime Spatial Planning
RFI	Request for Interest

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LIST OF SYMBOLS

A_{WF}	Wind farm area [km^2]
$A_{rotor,T}$	Rotor area of a wind turbine [m^2]
$D_{\parallel}$	Turbine distance in prevailing wind direction [m]
$D_{\perp}$	Turbine distance perpendicular to prevailing wind direction [m]
$P_{rated,T}$	Rated power capacity of a wind turbine [MW]
$P_{rated,WF}$	Rated power capacity of a wind farm [MW]
d^*	Mean relative turbine distance for a regular grid layout [$-$]
$d_{\parallel}$	Relative turbine distance in prevailing wind direction [$-$]
$d_{\perp}$	Relative turbine distance perpendicular to prevailing wind direction [$-$]
$p_{A_{WF}}$	Capacity density of a wind farm [MW/km^2]
$p_{A_{WF}}{}^*$	Corrected capacity density of a wind farm [MW/km^2]
$p_{A_{rotor}}$	Specific power of a wind turbine [W/m^2]
D	Rotor diameter of a wind turbine [m]
m	Number of wind turbines on the edge of a wind farm [$-$]
n	Number of wind turbines in a wind farm [$-$]
n^*	Corrected number of wind turbines in a wind farm [$-$]

1 INTRODUCTION

In order to reduce the greenhouse gas emissions of their electricity sector, most of the European countries in the North Sea region and the Baltic Sea region have defined national targets to increase their share of offshore wind power capacity.

The offshore wind energy sector competes with other maritime economic sectors on limited space resources. In most European countries national authorities have established a Maritime Spatial Planning (MSP) approach to coordinate spatial use and to ensure its environmental compatibility. Almost all of the neighboring countries of the North Sea region and the Baltic Sea region have already started or are currently planning to designate areas for the development of offshore wind energy projects. Matching the size of the designated areas with national offshore wind capacity targets requires assumptions for the prospective capacity density, which is here defined as the installed capacity per ground area.

What can be assumed for the capacity density of future offshore wind farms?

How do national regulatory frameworks differ?

This report analyzes capacity density on three levels. Section 2 reviews international assumptions for the determination of capacity densities on a theoretical level. Section 3 focuses on the planning level and summarizes national regulatory frameworks within the Baltic Sea and North Sea regions. Section 4 looks at the implementation level and analyzes existing offshore wind farms with respect to their capacity densities.

2 THEORY ANALYSIS AND LITERATURE REVIEW

The determination of a reasonable capacity density assumption for future offshore wind farms can be approached from different perspectives. In a first step, this section will focus on the theoretical level. It defines essential terms related to capacity density and identifies the relevant parameters. International capacity density assumptions are reviewed and summarized. Further, expected developments and influencing factors are highlighted.

2.1 DEFINITIONS

An **offshore wind farm** is a group of wind turbines that are located within a defined geographical area and that are electrically connected with the same substation.

The **capacity density** of a wind farm is defined as the ratio of the wind farm’s rated capacity to its ground area. Capacity density is expressed in megawatts per square kilometer. There is no natural upper limit for a wind farm’s capacity density.

Equation 1

$$p_{A_{WF}} = \frac{P_{rated,WF}}{A_{WF}}$$

$p_{A_{WF}}$	Capacity density of a wind farm $[\mathrm{MW/km^2}]$
$P_{rated,WF}$	Rated power capacity of a wind farm $[\mathrm{MW}]$
A_{WF}	Wind farm area $[\mathrm{km^2}]$

A wind farm’s capacity density alone does not allow any conclusions on its energy production. This requires the wind farm’s **capacity factor**, which is usually calculated as the yearly averaged power production divided by the rated power production.

Specific power defines a turbine’s specific rated power capacity per rotor area. It is expressed in watts per square meter.

Equation 2

$$p_{A_{rotor}} = \frac{P_{rated,T}}{A_{rotor,T}}$$

$$A_{rotor,T} = \frac{\pi \cdot D^2}{4}$$

$p_{A_{rotor}}$	Specific power of a wind turbine $[\mathrm{W/m^2}]$
$P_{rated,T}$	Rated power capacity of a wind turbine $[\mathrm{MW}]$
$A_{rotor,T}$	Rotor area of a wind turbine $[\mathrm{m^2}]$
D	Rotor diameter of a wind turbine $[\mathrm{m}]$

The distances between neighboring wind turbines in a wind farm define a wind farm’s **turbine spacing**. Usually, turbine spacing is depending on the prevailing wind direction.

$$d_{\parallel} = \frac{D_{\parallel}}{D}$$

$$d_{\perp} = \frac{D_{\perp}}{D}$$

$d_{\parallel}$	Relative turbine distance in prevailing wind direction $[-]$
$D_{\parallel}$	Turbine distance in prevailing wind direction $[\mathrm{m}]$
$d_{\perp}$	Relative turbine distance perpendicular to prevailing wind direction $[-]$
$D_{\perp}$	Turbine distance perpendicular to prevailing wind direction $[\mathrm{m}]$

Wind farm efficiency is here used as the ratio of actual energy production to theoretical energy production under the assumption that each wind turbine would experience undisturbed wind conditions.

2.2 RELEVANT PARAMETERS TO DETERMINE CAPACITY DENSITY

Assuming that in a wind farm a certain number of identical wind turbines are arranged in a rectilinear grid with congruent cells as shown in Figure 1, the wind farm's capacity density can also be calculated as follows:

Equation 3

$$p_{A_{WF}} = \frac{P_{rated,T}}{d_{\parallel} d_{\perp} D^2}$$

Inserting the relation for diameter and rotor area,

$$D^2 = \frac{4}{\pi} \cdot A_{rotor,T}$$

and Equation 2 gives:

Equation 4

$$p_{A_{WF}} = \frac{\pi}{4} \cdot \frac{1}{d_{\parallel} d_{\perp}} \cdot p_{A_{rotor}}$$

Capacity density is a function of specific power and turbine spacing.

Equation 4 shows that capacity density is a function of turbine spacing and specific power. Capacity density scales proportionally with specific power and inversely proportionally with the distances between adjacent turbines. These parameters will be discussed in the subsequent sections. Other parameters have only indirect impact on the capacity density of a wind farm.

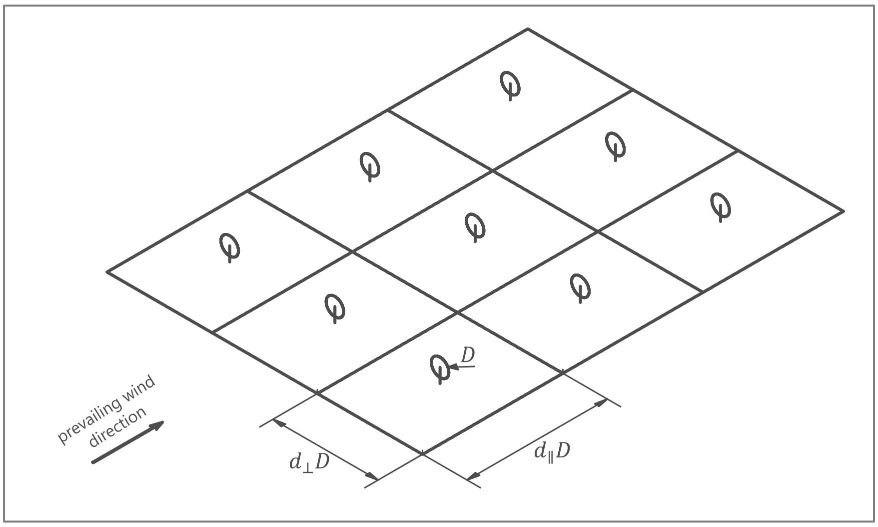


Figure 1:
Idealized wind farm layout and turbine spacing

Figure 1 shows an idealized wind farm layout. The area requirement per wind turbine is shown as rectangular ground area with the turbine in its center and determined by the respective turbine distance in prevailing wind direction and across prevailing wind direction.

The area indication of actual offshore wind farms might deviate from the approach used for Equation 3 and shown in Figure 1. The German Federal Maritime and Hydrographic Agency and other regulatory authorities define a wind farm’s area as the area that is described by the centers of the turbines that are positioned on the wind farm edges. This leads to a nominal increase of the capacity density. If we for instance consider a wind farm array of 10-by-8 turbines and equal turbine spacings in the prevailing wind direction and across to it this approach overestimates the capacity density by 27%. This effect becomes more significant for smaller wind farms. Moreover, capacity density becomes dependent of the size and shape of the wind farm. Because it is not general, this approach is not appropriate for scaling purposes and is therefore not considered in the studies that are analyzed in this section.

2.2.1 SPECIFIC POWER

As shown above, specific power is a main driver of capacity density. This section looks at specific power trends and current technology.

Offshore wind energy technology has shown a clear trend towards increased turbine sizes [see e.g. LBL 2016, IWES 2017, US-DOE 2017]. While global average installed turbine ratings and swept area have increased over the last years, a “modest trend towards lower specific power” [LBL 2016] can be observed. This resulted in higher average capacity factors. Figure 2 shows the specific power of offshore wind turbines that have been commissioned in European waters. The data supports the observation of a trend towards lower specific power.

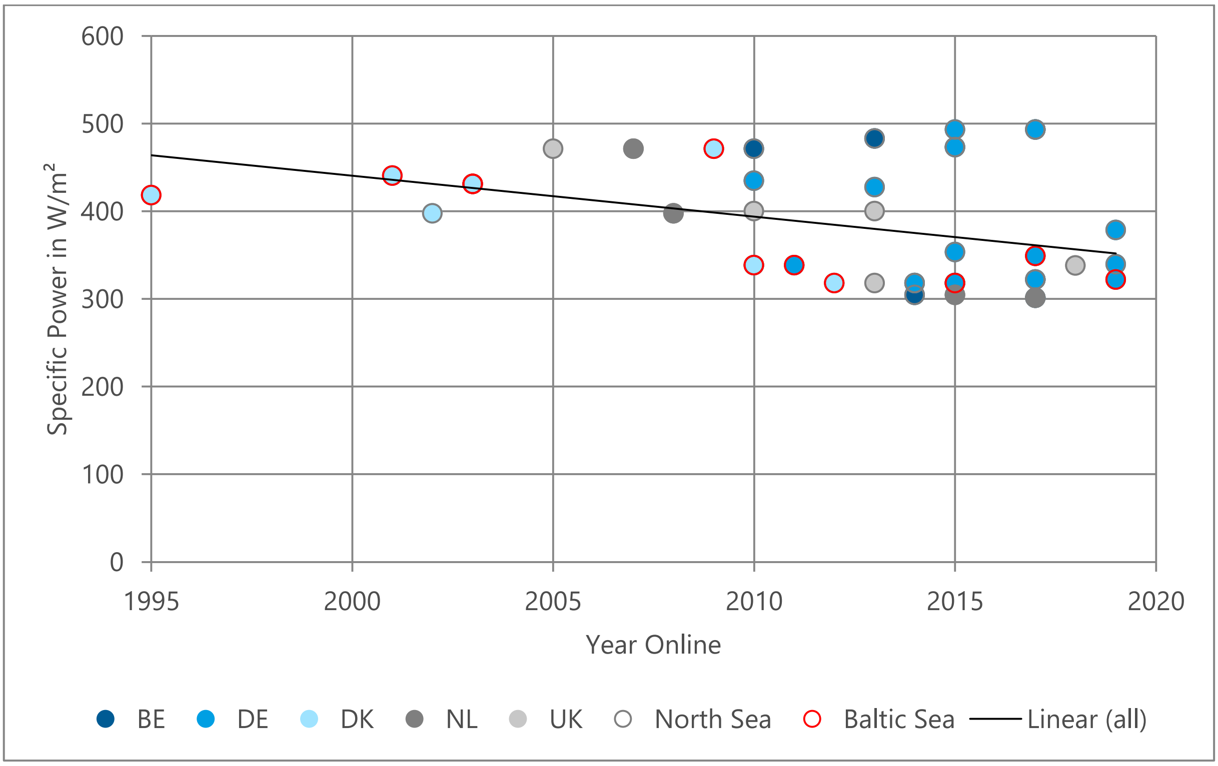
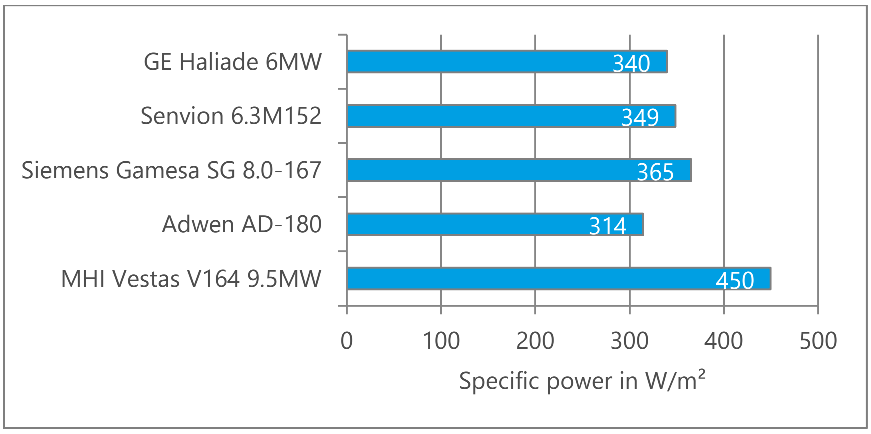


Figure 2:
Turbine specific power of European offshore wind farms

Figure 3 depicts the specific power ratings of recent offshore wind turbine models, which show a significant variance. Especially, *MHI Vestas' V164-9.5MW* stands out with a specific power of 450 W/m^2. The former 8 MW platform has been upgraded in 2017 making the *V164-9.5MW* the most powerful wind turbine for the present. In the past, manufacturers have upgraded a turbine model's power rating and rotor diameter successively. For example *Senvion's* (former *REpower*) offshore platform has initially been introduced with 5 MW and a 126 m rotor (401 W/m^2). First, the power has been upgraded to 6.15 MW (497 W/m^2), then the rotor has been enlarged to 152 m (342 W/m^2). It seems likely that *MHI Vestas* will increase the rotor diameter in the next step, again reducing the specific power.

Figure 3:
Specific power of major manufacturer’s recent wind turbine models (sorted by power rating; source: manufacturer’s data)



Specific power choice is site specific.

The choice of a suitable wind turbine is an economical decision and depends on the project specifics. Generally, turbines with high specific power make more sense in regions with high average wind speeds. To reach the same capacity factor, turbines with high specific power need higher wind speeds than turbines with low specific power.

Specific power of realized offshore projects is analyzed in section 4.

2.2.2 TURBINE SPACING

The second main driver of capacity density is turbine spacing. Turbine spacing is generally project specific and dependent on multiple input parameters. This section focusses on the correlation of turbine spacing and wind farm efficiency.

Wake losses can’t be avoided.

Turbine spacing is a critical issue because of the wake effect. The wake effect results from a turbine’s wind power extraction and leads to reduced wind speeds and increased turbulence, primarily in downstream direction. Wind turbines that are placed within the wake of a neighboring wind turbine will produce less power than under free-stream conditions. The wake of an offshore wind farm can extend for tens of kilometers [Platis et al. 2018, Volker et al. 2017]. Thus, wind farm efficiency losses due to the wake effect can’t be avoided in typical offshore wind farms with turbine spacing in the range of 5D to 15D.

Wake losses increase for narrower spacing.

Musial et al. [NREL 2013] analyzed the wake losses for various wind farm layouts within different areas (sizes between 100 km^2 and 175 km^2) off the U.S. east coast. For their analysis they use the OpenWind project layout tool. As a key finding they predict total wake losses in the range of 12% to 13% for 8D x 12D spacing. For 8D x 8D spacing total wake losses are predicted between 16% and 17%.

Wind farm efficiency depends on wind speed, wind farm area, and turbine spacing.

Volker et al. [Volker et al. 2017] simulated wind farm efficiencies for three different regions with different wind conditions using the Weather Research and Forecast model: Region A (onshore with a median wind speed of 7.4 m/s), Region B (offshore with a median wind speed of 9.1 m/s), and Region C (offshore with a median wind speed of 13.1 m/s). Wind characteristics for Region B are obtained at Horns Rev in Denmark and can be considered representative for typical wind farm locations in the North Sea region and the Baltic Sea region[1]. The authors use three different spacings: Wide (10.5D x 10.5D), Intermediate (7D x 7D) and Narrow (5.25D x 5.25D); and wind farm sizes in a range from 25 km^2 to 10^5 km^2. The results of Volker et al. confirm that wind farm efficiency drops when wind turbines are placed narrower[2]. The effect of turbine spacing on wind farm efficiency becomes less significant with increasing wind speeds. The results also show that the wind farm efficiency decreases significantly with increasing wind farm area. Therefore, the authors conclude that “in offshore regions, clusters of smaller wind farms are generally preferable”.

Turbine spacing is project specific.

To sum it up: every additional wind turbine that is placed within a designated wind farm area will increase the wind farm’s capacity density and with it the overall power production, but due to wake losses marginal gains are diminishing, leading to a decrease of the farm’s capacity factor. Similar to the choice of the turbine’s specific power, economically optimal turbine spacing is project specific. As will be shown in Sections 3 and 4, one key driver is the relevant regulatory framework, which often defines limits for a wind farm’s capacity and area. Other influencing factors are a project’s site characteristics like the wind speed distribution, or the distance to shore. But also the cost and compensation structure have to be considered when choosing a wind farm’s layout.

2.3 LITERATURE VALUES FOR CAPACITY DENSITY

Capacity density assumptions are frequently required for offshore wind resource potential analyses and offshore planning. This section recaps capacity density models and assumptions of four relevant sources.

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[1] For regional wind speed characteristics see e.g. https://globalwindatlas.info/

[2] For further details see Figure 5 in primary source.

In a recent study *BVG Associates* and *Geospatial Enterprise*s in order of *WindEurope* [BVG 2017] estimated the economically attractive offshore wind energy potential available to Europe. The authors conclude that by 2030 offshore wind could generate an Annual Energy Production (AEP) between 2,600 TWh and 6,000 TWh at competitive cost of €65/MWh. For the calculation of Europe's gross offshore wind potential a capacity density of 5.36 MW/km^2 is applied. This is derived from a specific power assumption of 368 W/m^2 and a spacing assumption of 9D x 6D. For the year 2030 a baseline wind turbine with a rotor diameter of 212 m and a power rating of 13 MW is applied. In an upside scenario a 15 MW wind turbine with a rotor diameter of 228 m is assumed.

In another study Müller et al. [Ecofys 2017] estimated the amount of offshore wind capacity that would be needed in European Seas by 2045 to meet the targets that were set by the United Nations at the Paris Climate Change Conference (COP21) in 2015. For the year 2045 the authors assume a 50% reduction in total energy demand (compared to 2010), a 45% electrification level, and a fully decarbonized electricity sector. As their key finding the authors estimate an offshore wind capacity target of 230 GW, of which 180 GW should be deployed in the North Sea. Müller et al. assume an average capacity of 5 MW/km^2 and an AEP of 4000 Full Load Hours (FLH). The Dutch Borssele wind farm area is named as reference. No specific power or turbine spacing assumptions are published.

The *Danish Energy Agency ENS* [ENS 2016] and *Energinet.dk*, the Danish transmission system operator, regularly publish technology catalogues for the purpose of energy planning. For large offshore wind turbines a capacity density of 5.4 MW/km^2 is assumed. The authors assume that turbine power rating will increase from 8 MW in 2015 (year of final investment decision) to 15 MW in 2050. While specific power is assumed to decline from 379 W/m^2 in 2015 to 332 W/m^2 in 2050, the authors expect that the capacity density will stay unchanged at 5.4 MW/km^2 and give a 90% confidence interval from 4.9 MW/km^2 to 5.9 MW/km^2. Consequently, a turbine's space requirement is assumed to stay unchanged in terms of space per rated power but to decline in terms of space per rotor area.

Musial et al. [NREL 2016] assessed the offshore wind energy potential for the United States under support by the *U.S. Department of Energy*. For calculating the gross potential a capacity density of 3 MW/km^2 is assumed. This assumption is based on developer input for U.S. projects [NREL 2013]. The authors had confidential access to nine developer responses to a Request for Interest (RFI) and to six responses to a Call for Information and Nomination (Call)[3] that were published by the *U.S. Bureau of Ocean Energy Management* in 2010 and 2012. While the capacity density was in a range from 3.28 MW/km² to 6.29 MW/km² with an average value of 3.81 MW/km² for the RFI, it was in a range from 1.64 MW/km² to 3.10 MW/km² with an average value of 2.78 MW/km² for the preceding Call. The concluding assumption for an average capacity density of 3 MW/km² is in line with the assumptions made in the *Department of Energy's Wind Vision* [US-DOE 2015]. For the calculation of the gross capacity factor a generic 6 MW turbine is assumed with a rotor diameter of 155 m and a specific power of 318 W/m². A turbine spacing of 7D x 7D is chosen in a 10-by-10 turbine array, corresponding to a capacity density of 5.1 MW/km². This deviates from the 3 MW/km² assumption and is chosen to compensate for array buffers and other setbacks.

Table 1:
Capacity density assumptions

Study	Focus Region	Focus Year	Specific Power Assumption	Turbine Spacing Assumption	Capacity Factor Assumption	Capacity Density Assumption
[BVG 2017]	Europe	2030	368 W/m²	9D x 6D	46.7% (baseline scenario) 47.0% (upside scenario)	5.36 MW/km²
[Ecofys 2017]	Europe	2045	n/a	n/a	45.7% (4000 FLH)	5 MW/km²
[ENS 2017]	Denmark	2015 2020 2030 2050	379 W/m² 353 W/m² 346 W/m² 332 W/m²	n/a	50% 51% 53% 56%	5.4 MW/km² 5.4 MW/km² 5.4 MW/km² 5.4 MW/km²
[NREL 2016]	United States	2016	n/a (318 W/m²)*	n/a (7D x 7D)*	site specific estimation	3 MW/km² (5.1 MW/km²)*

*deviating assumptions for capacity factor calculation

Table 1 summarizes the capacity density assumptions of four different sources. All three sources that cover European sea regions use consistent capacity density assumptions with only minor variances in a range from 5 MW/km² to 5.4 MW/km². The only source that could be identified for American waters

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[3] For further information see: https://www.boem.gov/Maryland/

uses a significantly lower capacity density of 3 MW/km^2. Still, deviating assumptions for site specific capacity factor estimation are in line with the results for European regions.

2.4 PROSPECTIVE DEVELOPMENTS

A reasonable prognosis for the development of offshore capacity densities is hard to provide, since capacity density depends on various techno-economic and regulatory parameters. This section highlights expert expectations and views with respect to the developments of specific power and capacity density.

Experts expect specific power to remain constant.

Wiser et al. [Wiser et al. 2016] conducted a survey of 163 wind energy experts on their views of possible wind energy cost reductions in the future. The authors summarize, that “expected turbine capacity ratings (and hub heights) grow significantly, but ratios of rotor swept area to nameplate capacity remain roughly constant”.

Specific power should decrease for steadier output generation.

In a recent study Knorr et al. [IWES 2017] analyzed the relevance of offshore wind for the transformation of the German energy system. The authors argue that offshore wind power can make a relevant contribution to a 100% renewable energy system. Therefore, a more constant electricity generation would be required from wind and other fluctuating sources. For wind energy, this could be reached by an increase in rotor area, which results in a decrease of specific power. For their simulation Knorr et al. assume representative turbines for the years 2030 and 2050. While a specific power of 365 W/m^2 is assumed for the year 2030, the authors expect that specific power will have to decrease to 325 W/m^2 by 2050. This would lead to a significant increase of the capacity factor.

Lower specific power can be economically beneficial.

For the same rotor area, turbines with a high specific power rating have higher cost per rotor area but do also lead to a higher AEP, because they produce extra energy at high wind speeds, when low specific power turbines already operate in power reduction mode. When wind speeds are high, electricity systems with a high penetration of wind energy capacity are often characterized by wind power abundance which leads to a decrease of spot market electricity prices. In a free market, marginal gains for an increase in specific rating are therefore diminishing.

This finding is supported by Hirth & Müller [Hirth & Müller 2016], who compare “advanced” wind turbines that have lower specific power ratings with “classical” wind turbines. The authors conclude that advanced turbines generate power more constantly and can thus “substantially increase the spot market value of generated electricity”. In an electricity system with a high wind power penetration of 30%, the authors estimate a bulk power value increase of 15% for “advanced” wind turbines. Additionally, advanced wind turbines could help reduce cost for grid investments and balancing.

In former times, wind power has often been subsidized on a MWh-basis, which eliminated market effects like the time variability of electricity power values and supported higher specific ratings. In 2017 offshore tenders in Germany have been won with €0/MWh bids[4]. These zero-subsidy bids make spot market revenues especially important for investors. This could lead to a decrease in specific power of the dominant offshore wind turbine technology.

As shown in Equation 4, capacity density scales directly with specific power. If specific power will decrease in the future, capacity density should also decrease (assuming that turbine spacing will stay at current levels). The Danish Energy Agency [ENS 2016] expects that specific power will decrease in the future, while capacity density is expected to remain unchanged (see Table 1). This would mean that the decrease of specific power would be compensated by narrower turbine spacing.

The findings of Knorr et al. [IWES 2017] and Hirth & Müller [Hirth & Müller 2016] show that prospective developments of specific power installations and capacity density will be highly dependent on policy frameworks and offshore regulations.

3 NATIONAL PLANNING APPROACHES AND STANDARDS

This section analyzes national differences in the capacity densities of realized wind farms in five European countries and summarizes their current regulatory frameworks with respect to the capacity density.

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[4] https://www.bundesnetzagentur.de/SharedDocs/Pressemitteilungen/DE/2017/13042017_WindSeeG.html

3.1 NATIONAL DIFFERENCES IN CAPACITY DENSITY

As has been mentioned in the previous section, capacity density choice is not a purely techno-economical decision. Instead, capacity density is driven by the regulatory framework defined by the respective national authorities. Figure 4 shows the capacity densities of realized offshore wind farms in the five European countries that have the most experiences with offshore wind.

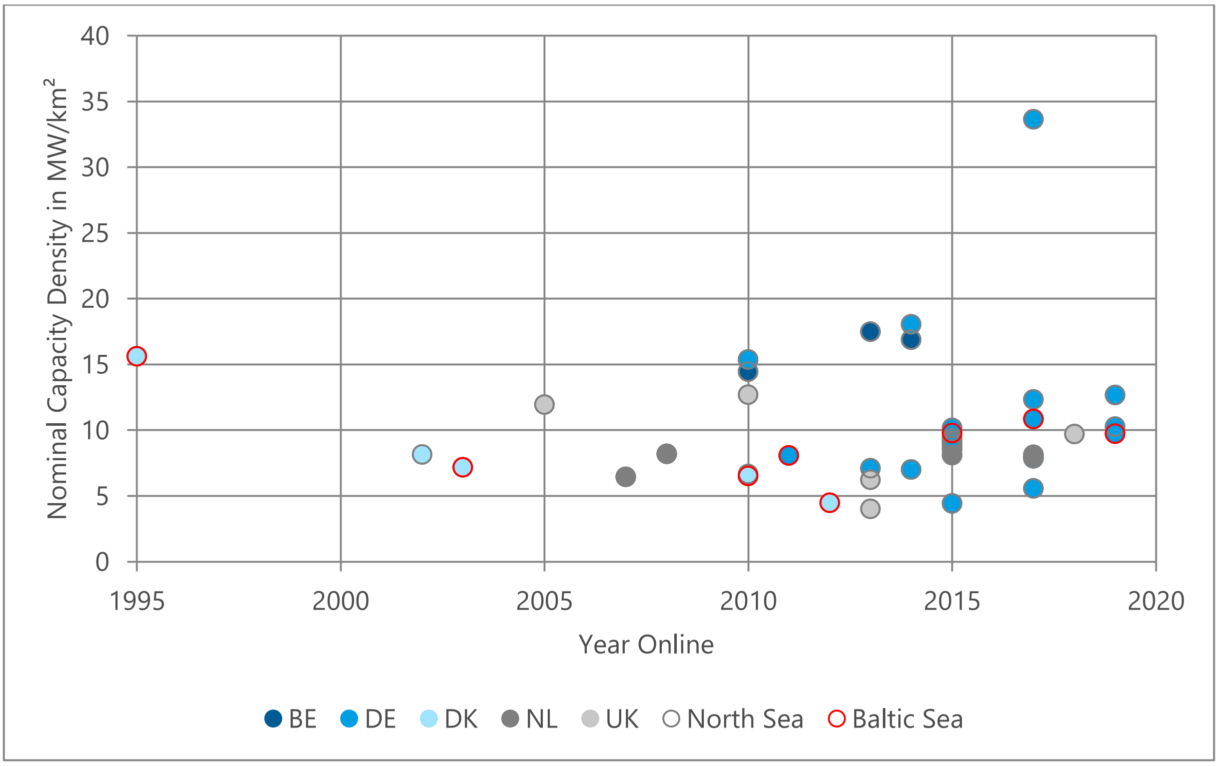

Figure 4:
Nominal capacity densities of European offshore wind farms

Two major conclusions can be drawn from this analysis:

1) Wind farm capacity densities show high variances and significant differences exist between national averages.
2) Most wind farms have a higher capacity density than the literature values presented in Section 2.3.

It is remarkable that in Germany and Belgium offshore wind farms have significantly higher capacity densities than the European average. For Belgium this can be explained by the regulatory framework. Due to the limited space resources the Belgian government, which is responsible for the awarding of offshore concessions, has obligated concessionaires to use the space granted as intensively as possible [BE 2000]. This resulted in capacity densities that are among the highest in Europe.

Also German offshore wind farms have comparably high capacity densities. Germany has relatively few offshore space resources when compared to The United Kingdom or Denmark. Because of competing wind farm projects, other competing maritime economic sectors and strong regulatory restrictions, offshore wind sites are often segmented into small areas. In the beginning of offshore planning for German sites, pilot offshore farms were limited to 80 turbines. To maximize a wind farm's AEP the projects were often planned with the full number of turbines. This led to a rather narrow turbine spacing. Additionally, most project developers planned to use the most powerful turbine technology that was expected to be available. Typical were 5 MW platforms, for instance the turbine types *REpower 5M* or *Areva M5000*, which have a high specific power rating of 401 W/m^2 and 473 W/m^2 respectively. In contrast, offshore farms in Denmark were at the same time typically planned with low power density turbine types such as *Siemens SWT-2.3-93* (339 W/m^2).

In Germany the permission of offshore wind farms used to be a multi-step process with long planning durations. When offshore wind planning started, experiences were only available from onshore wind farms. For this reason offshore wind farms were planned with similar spacing assumptions. The first realized projects showed that increased efficiency losses due to the lower wind turbulence offshore have been underestimated.

The major reason for the differences between literature values and realized wind farms' capacity densities is the difference in area indication as explained in Section 2.2. Other reasons are national specifics as explained above.

3.2 CURRENT REGULATORY STATUS IN EUROPEAN COUNTRIES

This section analyzes European regulatory frameworks for offshore wind farms with respect to a wind farm's capacity density. The analysis covers Denmark, Germany, Belgium, The Netherland and The United Kingdom. No relevant publicly available information could be identified for the other countries in the North Sea and Baltic Sea region. Also consultation of national experts revealed no relevant regulatory specifics.

3.2.1 DENMARK

The conditions for offshore wind farms are laid down in the Promotion of Renewable Energy Act [DK 2009]. In Denmark there are two different procedures to develop offshore wind projects: a tender procedure that is run by the Danish Energy Agency[5] and an open-door procedure.

In the open-door procedure developers can take the initiative and choose a specific site. Developers then need to make an application for a license to carry out further investigations.

In Denmark a minimum capacity density of 4.55 MW/km^2 is required.

Danish tender sites are divided into offshore sites and near shore sites. Wind, wave and soil conditions are investigated under supervision of the Danish Energy Agency. The tender conditions define a specific wind farm capacity for each tender. For the latest offshore tenders capacities were 400 MW (±10 MW) for *Horns Rev 3* [ENS 2013] in the North Sea and 600 MW (±10 MW) for *Kriegers Flak* [ENS 2016b] in the Baltic Sea. Projects can only be developed within a designated area and are additionally limited to a maximum space requirement of 0.22 km^2/MW [ENS 2016c], which corresponds to a minimum capacity density of 4.55 MW/km^2. Concessions are awarded to the tenderer quoting the lowest price per kilowatt hour.

Project realization shows that developers tend to use as much space as possible to bring down LCOE. For instance, *Anholt*[6] (Baltic Sea) was realized with a capacity of 399.6 MW on an area of 88 km^2 (4.54 MW/km^2)[7]. *Horns Rev 3*[8] (North Sea) is announced to be built with a capacity of 406.7 MW on an area of 88 km^2 (4.62 MW/km^2).

3.2.2 GERMANY

Capacity density used to be a developer's choice in Germany.

In the beginning of German offshore wind development, the choice of a wind farm's site and area as well as its capacity rating has been made by the project developer. Wind farm projects were consented by the Federal Maritime and Hydrographic Agency if they were located within the exclusive economic zone, which is the case for most of the projects in Ger-

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[5] For further information see https://ens.dk/en/our-responsibilities/wind-power

[6] https://stateofgreen.com/files/download/5199

[7] This is below the allowed value. The difference most likely results from rounding errors.

[8] https://corporate.vattenfall.com/press-and-media/press-releases/2017/construction-begins-on-horns-rev-3/

many. Projects within coastal waters (12 nautical mile zone) were consented by the respective state authorities. This procedure was characterized by a complex and long-lasting multi-step application process. When different projects were competing for the same area, an early application could be a critical factor for consent approval. Because of the fixed subsidies under the Renewable Energy Act, a high energy yield has been attractive for project developers. If space resources were limited this could lead to a high capacity density.

From 2026 on pre-developed sites will be tendered.

Since 2017 Germany is moving towards a centralized tender regime. Wind farms that will go online from 2026 will have to win a tender for a pre-developed offshore site. It is planned that a capacity of 700 MW to 900 MW will be tendered annually. The tender site will be detailed in the so-called *site development plan*. The subject of the site development plan is outlined in the *WindSeeG, Section 5* (DE 2016). Among other details, the site development plan will contain offshore wind farm sites and the likely amount of capacity to be installed in stipulated sites. That indicates that the capacity of a specific site will be limited or even fixed, which leads to an implicit limitation or fixation of the capacity density. Awards will be issued for the lowest bid.

For wind farm projects that plan to go online between 2021 and 2025 a transition regime has been established. Only projects with an advanced planning status are qualified to participate in the tender. Tenders are awarded on the basis of the lowest bid given as price per kilowatt-hour. In a first bidding round an overall capacity of 1,490 MW has been awarded for prices from 0.0 ct/kWh to 6.00 ct/kWh.

3.2.3 THE NETHERLANDS

The Dutch Government has designated several zones for the construction of offshore wind farms laid down in the Netherland Offshore Wind Energy Act [NL 2015]. Wind farms are only allowed in these zones. Each zone consists of different sites, which are consented and tendered by the Government. The sites' wind, water and soil conditions are investigated by the Government [RVO 2015]. The data collection and tendering procedure are organized by the Netherlands Enterprise Agency[9]. By defining both site area and capacity density the Dutch authorities implicitly define the allowed capacity density.

In The Netherlands site specific capacity density ranges are defined implicitly.

In the latest tender round the Hollandse Kust (zuid) wind farm sites (HKZWFS) I and II have been tendered. For the first time such a tender was only opened for zero-subsidy bids. The tender has been closed on December 21, 2017. Specific rules have been defined in a Ministerial Order [NL 2017]. Regardless of the different site areas (HKZWFS I is 18% bigger than HKZWFS II) equal limits have been defined for the allowed wind farm capacity. This results in allowed capacity densities in the range of 6.05 MW/km² to 8.02 MW/km². No reason is given for the choice of the capacity density.

Table 2:
Dutch 2017 offshore tender specifics

Site	Effective Area	Capacity Limits	Resulting Capacity Density Limits
HKZWFS I	56.5 km²	342 MW – 380 MW	6.05 MW/km² - 6.73 MW/km²
HKZWFS II	47.7 km²	342 MW – 380 MW	7.22 MW/km² - 8.02 MW/km²

Higher capacity densities are preferred.

The Ministerial Order further specifies ranking criteria and their weightings. One criterion (maximum score: 10/100) is the capacity density. Higher capacity is preferred, which incentivizes developers to maximize capacity density within the given limits. Another criterion (maximum score: 10/100) is the social cost measured as P50 value of the net electricity production. Higher production is preferred, which also stimulates high capacity densities.

3.2.4 BELGIUM

In Belgium an offshore area in the North Sea has been reserved for the production of renewable energy, designated by the Royal Decree of May 17, 2004 [BE 2004]. This area has been subdivided into eight concessions which have all been awarded to project developers.

In Belgium offshore sites have to be used as intensively as possible.

State concessions for the development and operation of offshore wind farms are awarded on the basis of the selection and award criteria set out in the Royal Decree of December 20, 2000 [CREG 2015]. Article 14 defines a number of obligations for the concessionaires [BE 2000]. One obligation is to use the space granted as intensively as possible (Art 14, 10°). This obligation is justified by the scarcity of offshore space in Belgium. Therefore the highest energy density (expected AEP per

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[9] For further information see https://offshorewind.rvo.nl/

area) is targeted when state concessions are awarded. This obligation requires a high capacity density. In its report the Belgian Commission for Electricity and Gas CREG [CREG 2015] states that the mentioned criteria lead to high energy densities but also comparably high levelized cost of electricity due to low capacity factors. According to CREG, the decision whether high energy densities or low energy costs should be prioritized in Belgium is a political one.

3.2.5 THE UNITED KINGDOM

In the United Kingdom the selection of offshore wind farm sites has lastly been organized in two stages. In the first stage zones for wind farm development were defined by The Crown Estate. In stage two, project developers identified suitable sites within those zones.

The Crown Estate has the right to lease areas of seabed for offshore wind farms in The United Kingdom. In its latest offshore wind program called ‘Round 3’ The Crown Estate identified nine zones likely to be suitable for wind farms [UK 2013]. In a next step a competitive tender was run for the rights to search for possible wind farm sites within these zones. These rights were awarded to nine consortia in 2010. In the second stage the project developers identified suitable sites taking into account technical and environmental issues and applied for consent. No limits for site area, wind farm capacity or capacity density have been defined by the regulating authorities. Those specifics are set by the project developers themselves as a result of their internal project optimization.

The Crown Estate recently announced that it considers new leasing for offshore wind. Today it is not clear, what will be the conditions for the next leasing round.

3.2.6 SUMMARY

The comparison of regulatory frameworks in five European countries shows that regulation of offshore wind farms can have two competing objectives. It can either promote a high energy yield per sea area or low electricity prices. Table 3 summarizes the specifics of the different frameworks.

Table 3:
Regulatory frameworks in European countries

	Site	Area	Capacity	Capacity Density	Primary Incentive
BE	Fixed	Fixed	Developer's decision	Developer's decision	High energy density
DE	Developer's decision	Developer's decision	Developer's decision	Developer's decision	High energy density
	Pre-developed (from 2026)	Fixed	Limited or Fixed	Limited or Fixed	Low LCOE
DK	Pre-developed	Limited (max)	Fixed	Limited (min)	Low LCOE
NL	Pre-developed	Fixed	Limited (min/max)	Limited (min/max)	Low LCOE
UK	Developer's decision within designated zones	Developer's decision	Developer's decision	Developer's decision	Low LCOE

4 LAYOUT OF REALIZED OFFSHORE WIND FARMS

The previous section shows that capacity density varies between wind farms and nations. This section provides a detailed analysis of the capacity density and its drivers for 43 realized offshore wind farms.

4.1 APPROACH

The analysis is conducted on the basis of the individual turbines' geographical coordinates. Wherever possible, coordinates were obtained from official sources like the respective national authorities [ENS 2018, BSH 2018, BNetzA 2018, FOD Economie 2018]. Coordinates for Dutch offshore wind farms were obtained from a third party source [Bosch & van Rijn 2018]. For British offshore wind farms, extensive data is presented online [The Crown Estate 2018] but not provided for download. Data for some British wind farms as well as early German wind farms has been obtained from the OpenStreetMap database [OSM 2018]. All geographical coordinates have been transformed to the Universal Transverse Mercator (UTM) format.

The analysis covers 43 offshore wind farms from five countries that have been or will be fully commissioned between 1995 and 2019.

4.1.1 AREA CALCULATION

The wind farm area is calculated using Delaunay Triangulation as proposed by the Danish Energy Agency [ENS 2016c]. Triangles that have a squared circumradius value of 2 km^2 or more are eliminated. Otherwise, the areas of windfarms with concave hulls are overestimated. Figure 5 shows the result of the area calculation for the Danish offshore wind farm *Rødsand 2* (DK, Baltic Sea). The sum of all triangle areas amounts to 31.72 km^2 and is therewith in line with the results published by ENS.

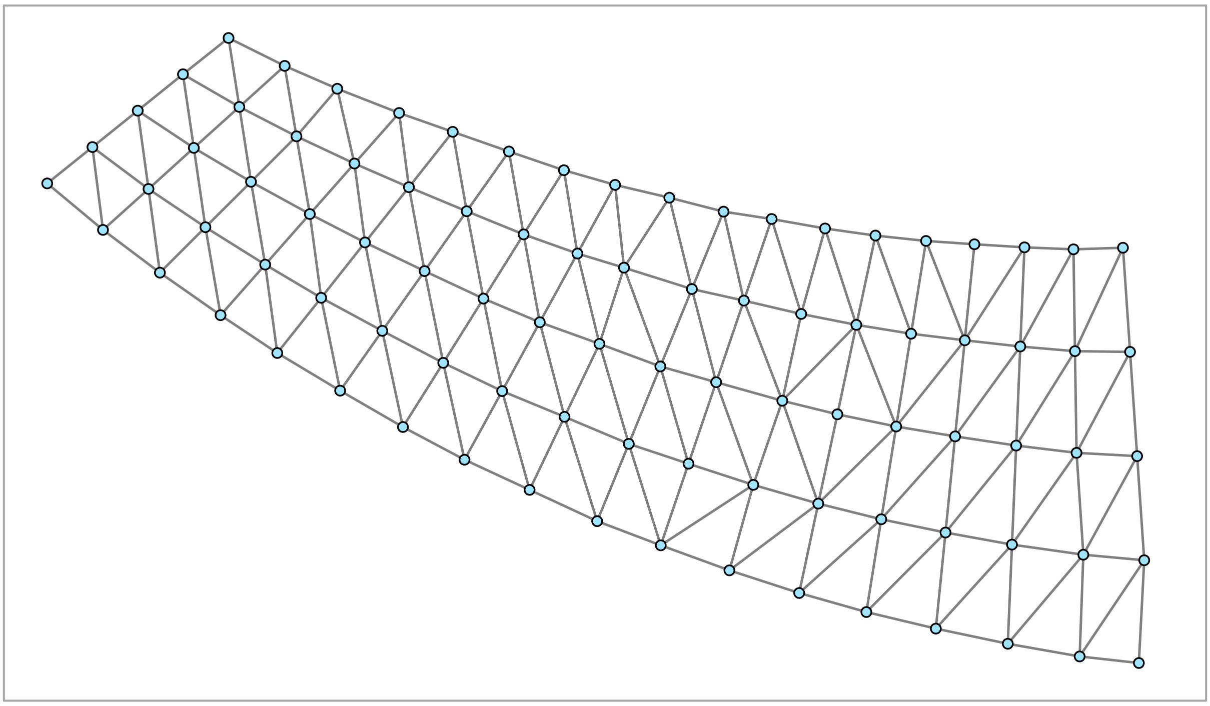


Figure 5:
Exemplary area calculation for *Rødsand 2* (DK, Baltic Sea) using Delaunay Triangulation

For wind farms that have a single line layout, no area or area derived indicators have been calculated.

4.1.2 CAPACITY DENSITY CORRECTION

Scalability and comparability require a capacity density correction.

The nominal capacity density can be calculated by simply dividing the wind farm's overall capacity by its area. As argued before, this leads to an overestimation of the capacity density, especially for smaller wind farms. For this reason a corrected wind farm capacity density is calculated to make the wind farms comparable to each other and to the literature values. To account for the reduced number of rectangles that are created by the centers of the wind turbines, a reduced number of wind turbines is considered for the calculation of the wind farm capacity. In a two dimensional array of x times y turbines, the number of created rectangles is $(x-1)\cdot(y-1)$, the total number of turbines is $n = x \cdot y$, and the number of turbines on the edges of the wind farm is $m = 2\cdot(x+y-1)$. Since most of the wind farms are not realized in a regular grid layout, a more general approach is used. The reduced number of wind turbines is defined to correspond to the amount of created rectangles in a wind turbine array.

$$n^* = (x-1)\cdot(y-1) = n - \left(\frac{m}{2}+1\right)$$

n^*	Corrected number of wind turbines in a wind farm $[-]$
n	Number of wind turbines in a wind farm $[-]$
m	Number of wind turbines on the edges of a wind farm $[-]$

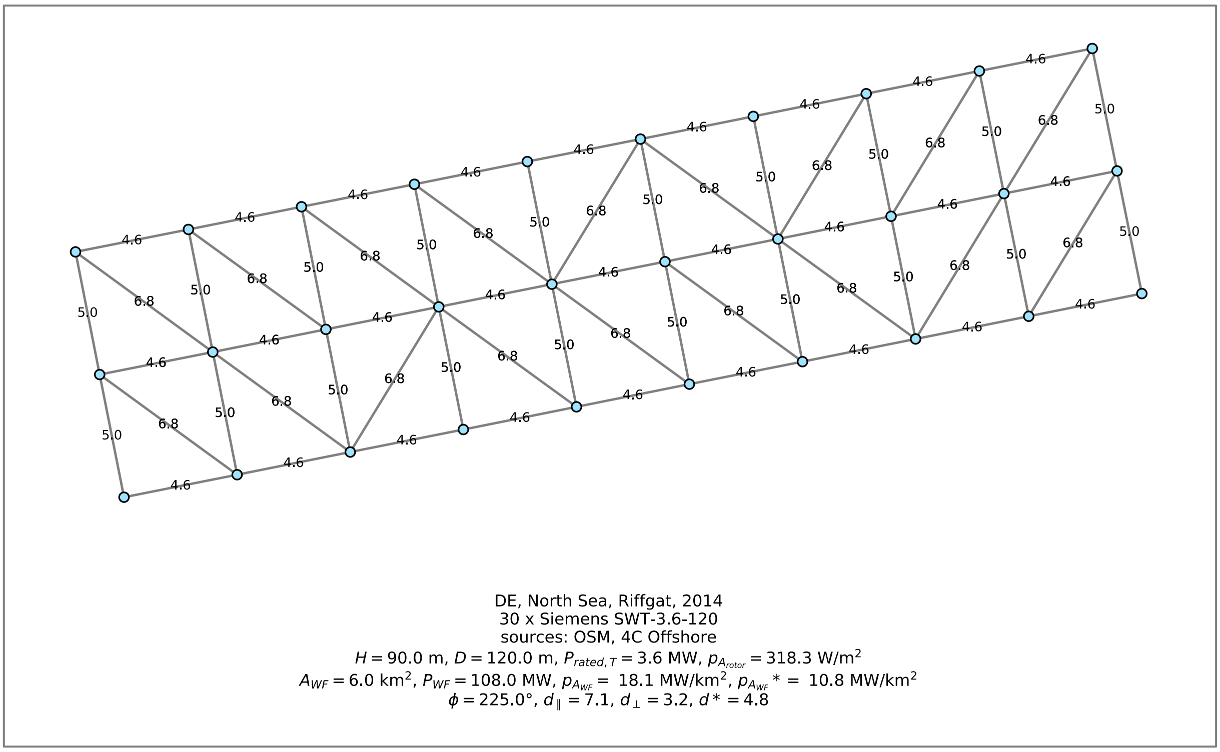
Now the corrected capacity density can be calculated as follows:

$$p_{A_{WF}} * = \frac{n^* \cdot P_{rated,T}}{A_{WF}}$$

$p_{A_{WF}} *$	Corrected capacity density of a wind farm $[\mathrm{MW/km^2}]$

For the example of *Riffgat* capacity density is reduced from 18.1 MW/km² to 10.8 MW/km².

This approach shall be explained for the example of the wind farm *Riffgat* (DE, North Sea). If we require wind farm scalability, the space that is available for a single wind turbine is here represented by a rectangle of $5.0D$ times $4.6D$. Still, the area that is taken into account for the calculation of the nominal capacity density only amounts to 18 of such rectangles for a total of 30 turbines. If we apply the equation above, 18 turbines are considered for the calculation of the wind farm's total capacity. Hence, the nominal capacity density of $18.1\ \mathrm{MW/km^2}$ is reduced to a corrected capacity density of $10.8\ \mathrm{MW/km^2}$. This eliminates the effects of wind farm size and shape and allows for wind farm scaling.



DE, North Sea, Riffgat, 2014
30 x Siemens SWT-3.6-120
sources: OSM, 4C Offshore
$H = 90.0$ m, $D = 120.0$ m, $P_{rated,T} = 3.6$ MW, $p_{A_{rotor}} = 318.3$ W/m^2
$A_{WF} = 6.0$ km^2, $P_{WF} = 108.0$ MW, $p_{A_{WF}} =$ 18.1 MW/km^2, $p_{A_{WF}}* =$ 10.8 MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 7.1$, $d_{\perp} = 3.2$, $d* = 4.8$

Figure 6:
Space per wind turbine for *Riffgat* (DE, North Sea)

4.1.3 TURBINE SPACING ANALYSIS

Ellipses represent turbine distances in the prevailing wind direction and across to it.

Turbine spacing parameters are provided as the direct relative distances between neighboring wind turbines (see Appendix). Additionally, distances are analyzed with respect to the prevailing wind direction. These distances are determined using oriented ellipses that expand until they reach the next neighboring turbines. The average turbine spacing in main wind direction ($d_{\parallel}$) is calculated from the average of the ellipses' semi-major axes. Average turbine spacing across the prevailing wind direction ($d_{\perp}$) is calculated from the average of the ellipses' semi-minor axes. An ellipse's semi-major axis is defined to be longer than or equal to its semi-minor axis. Ellipses with an aspect ratio higher than 3 are not considered for average calculation. Otherwise turbines on the corners of a wind farm might distort the average values. Southwest ($\varphi = 225°$) is assumed as prevailing wind direction for all wind farms. Figure 7 shows the resulting ellipses for the wind farm *EnBW Baltic 2* (DE, Baltic Sea).

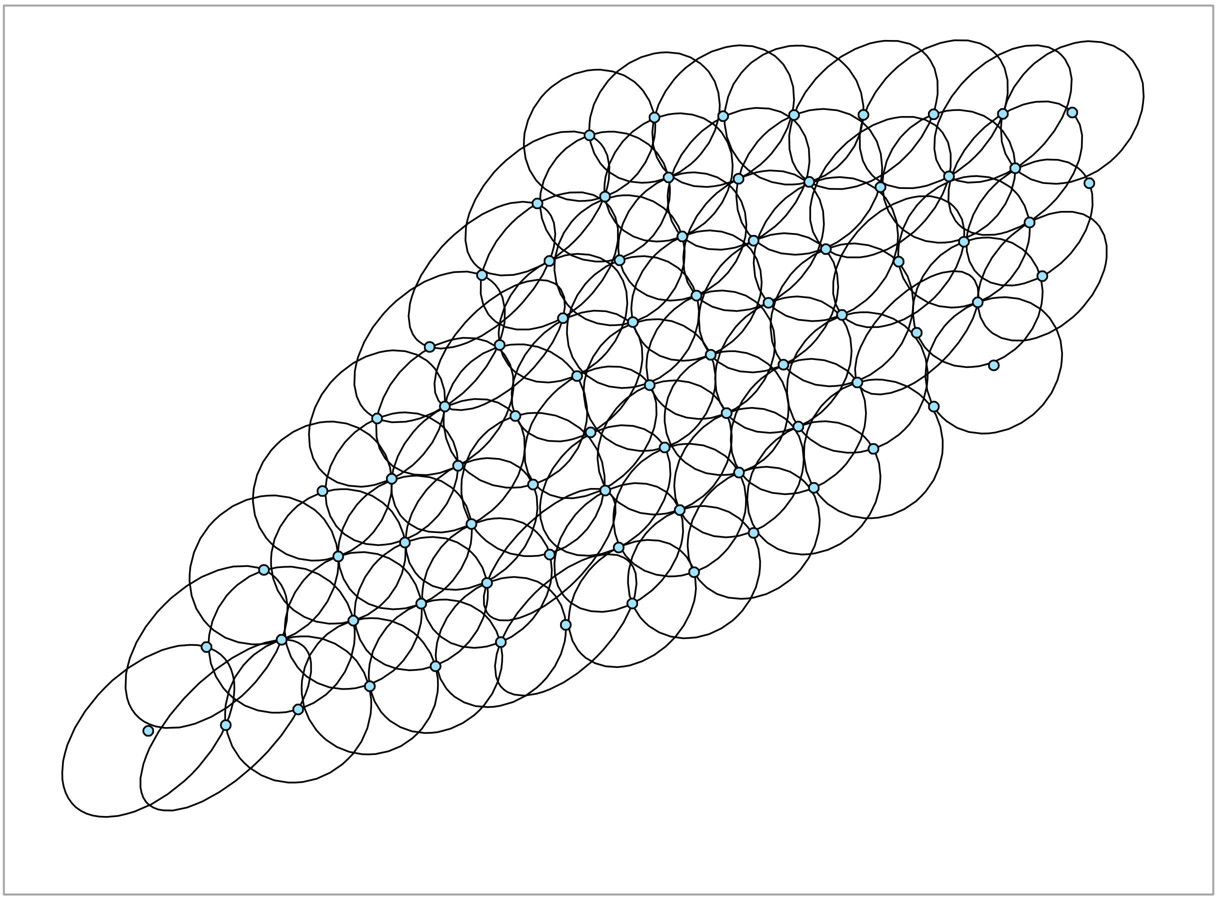


Figure 7:
Exemplary determination of turbine distances parallel and perpendicular to the prevailing wind direction for *EnBW Baltic 2* (DE, Baltic Sea).

The distance parameters that have been introduced in the preceding paragraph are not eligible for the back-calculation of a wind farm's capacity density because they are very sensitive to the farm layout and the wind direction. Therefore another synthetic distance parameter is derived from Equation 4, which assumes that all wind turbines of a wind farm would be organized in a rectilinear grid with the same spacing parallel and across to the prevailing wind direction.

$$d^* = \sqrt{\frac{\pi}{4} \cdot \frac{p_{A_{rotor}}}{{p_{A_{WF}}}^*}}$$

d^*	Mean relative turbine distance for a regular grid layout

This parameter is independent from a wind farm's size, shape, layout and prevailing wind direction and can thus be a good indicator to compare wind farms against each other. Figure 6 shows that this approach produces reasonable results if it considers the corrected capacity density.

4.2 RESULTS

The following paragraphs summarize the findings of the wind farm analysis. Further details for the individual wind farms are provided in the Appendix.

4.2.1 CORRECTED CAPACITY DENSITY

Figure 8 shows the corrected capacity densities for European wind farms. Two major observations can be made in comparison to the nominal capacity density:

1) The variance in capacity density is reduced. This is due to the effect, that differences in wind farm size and shape are isolated from the capacity density.

2) Capacity density values are lower and closer to the literature values presented in Section 2.3. The area weighted average capacity densities are 6.0 MW/km^2 for the North Sea and 5.5 MW/km^2 for the Baltic Sea.

The same figure identifies the respective sea basin of the selected wind farms. Average capacity density is higher in the North Sea than in the Baltic Sea. This is due to the fact, that the North Sea average value is strongly influenced by the Belgian and German wind farms with high capacity densities, while the Baltic Sea average value is strongly influenced by the Danish wind farms with low capacity densities. No general trend can be observed for the development of the capacity density.

Area weighted average values of the nominal and the corrected capacity densities in European countries are summarized in Table 4.

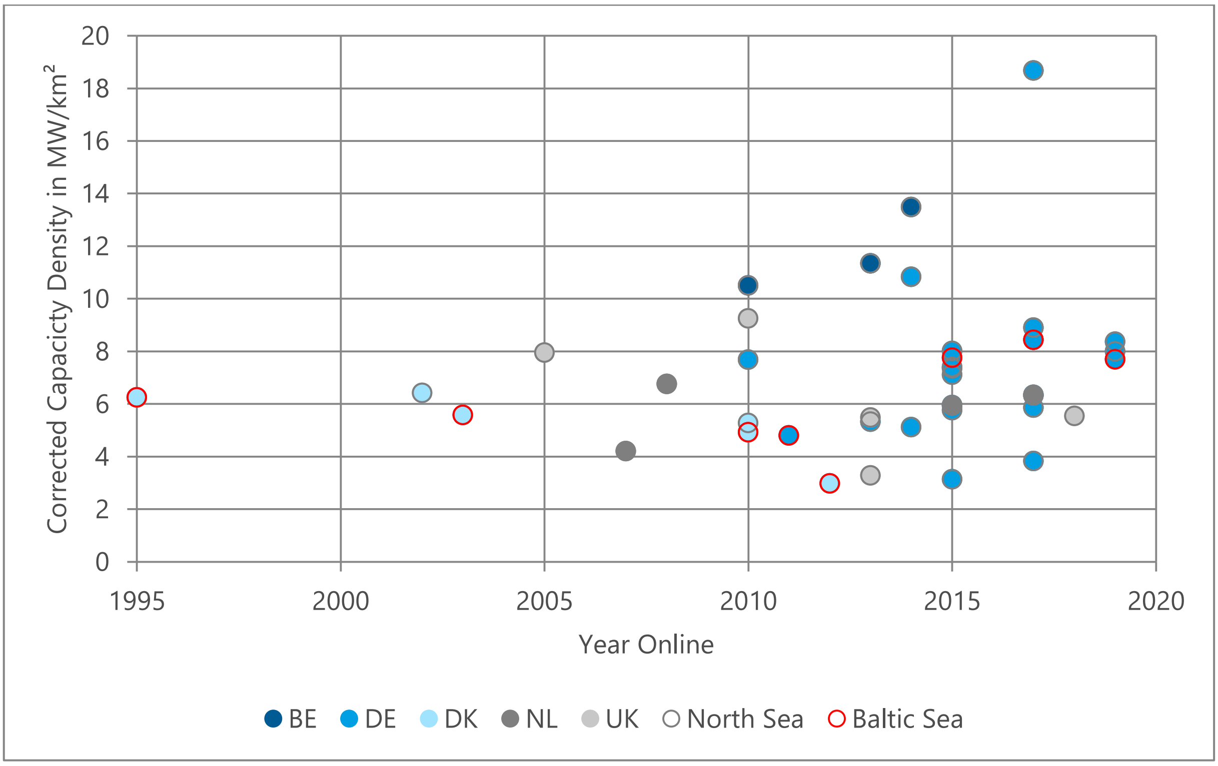


Figure 8:
Corrected capacity density of European offshore wind farms.

Table 4:
Comparison of nominal and corrected capacity densities in European countries (area weighted average)

Country / Sea Basin	Total Area in km²	$\overline{p_{AWF}}$ in MW/km²	$\overline{p_{AWF}}^*$ in MW/km²
BE	43	16.5	11.8
DE	751	8.7	6.5
DK	195	5.9	4.3
NL	121	7.9	6.0
UK	285	6.1	4.8
North Sea	1145	8.1	6.0
Baltic Sea	249	7.3	5.5

4.2.2 SPECIFIC POWER

Figure 9 shows that turbine specific power of European wind farms varies in a range from 300 W/m² to 500 W/m². Still, no significant correlation can be observed between turbine specific power and wind farm capacity density. Also, no national specifics can be observed.

Wind farms in the Baltic Sea region tend to use wind turbines with lower specific power rating than wind farms in the North Sea region. The slightly lower average wind speeds in the Baltic Sea region might be a reason for this.

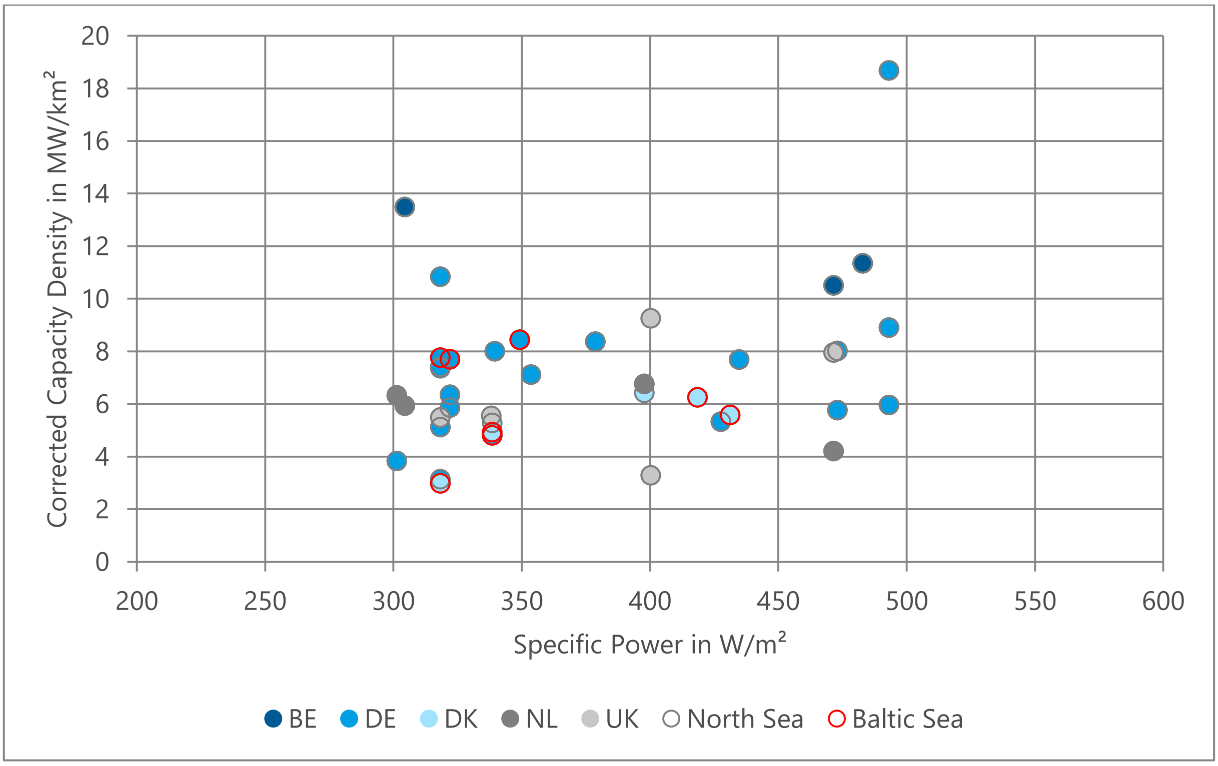


Figure 9:
Capacity density as a function of specific power

4.2.3 TURBINE SPACING

Figure 10 plots the average turbine spacing distances parallel and perpendicular to the prevailing wind direction. As expected, parallel distances (4.6D to 12.1D) are generally higher than perpendicular distances (3.2D to 8.0D).

The strong impact of turbine spacing on capacity density becomes clear from Figure 11, which plots corrected capacity density over mean turbine spacing. Wind farms with high capacity densities such as the Belgian farms do generally have low distances between turbines. On the contrary, wind farms with low capacity densities like the most Danish ones do generally have high distances between turbines. Especially in Germany spacing values vary quite significantly.

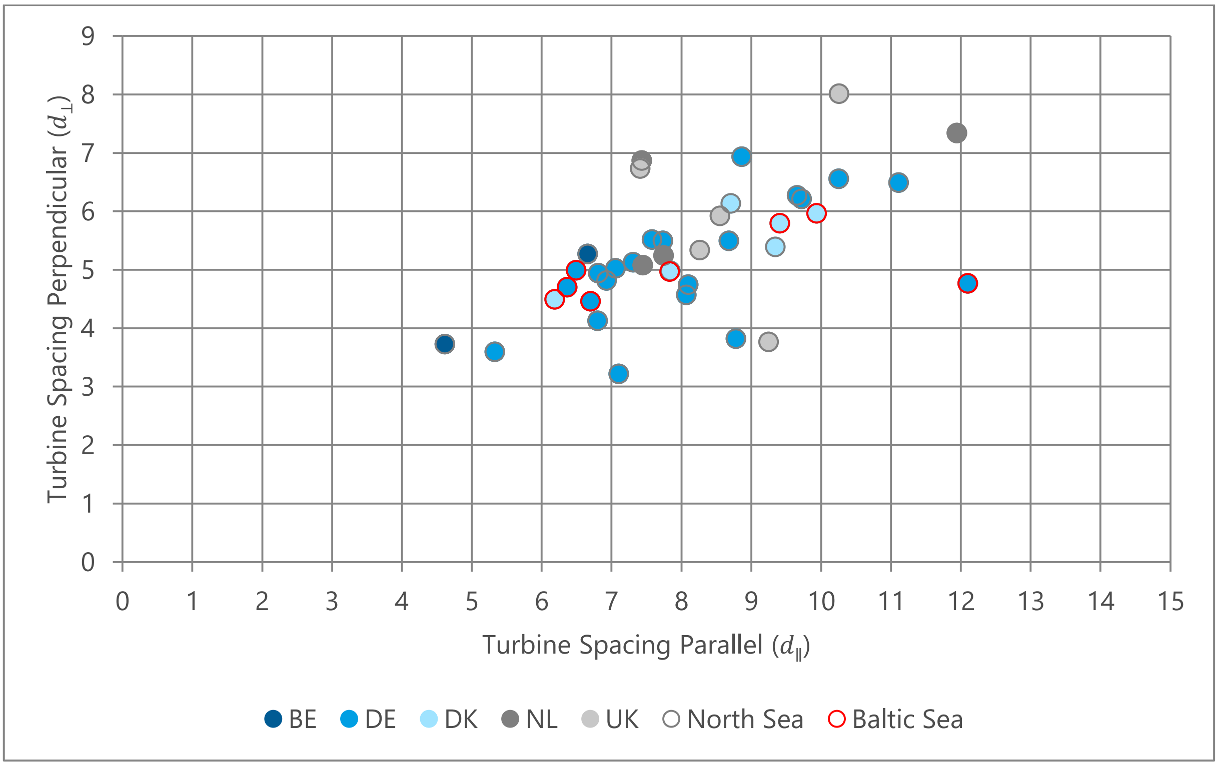


Figure 10:
Turbine spacing parallel and perpendicular to the prevailing wind direction

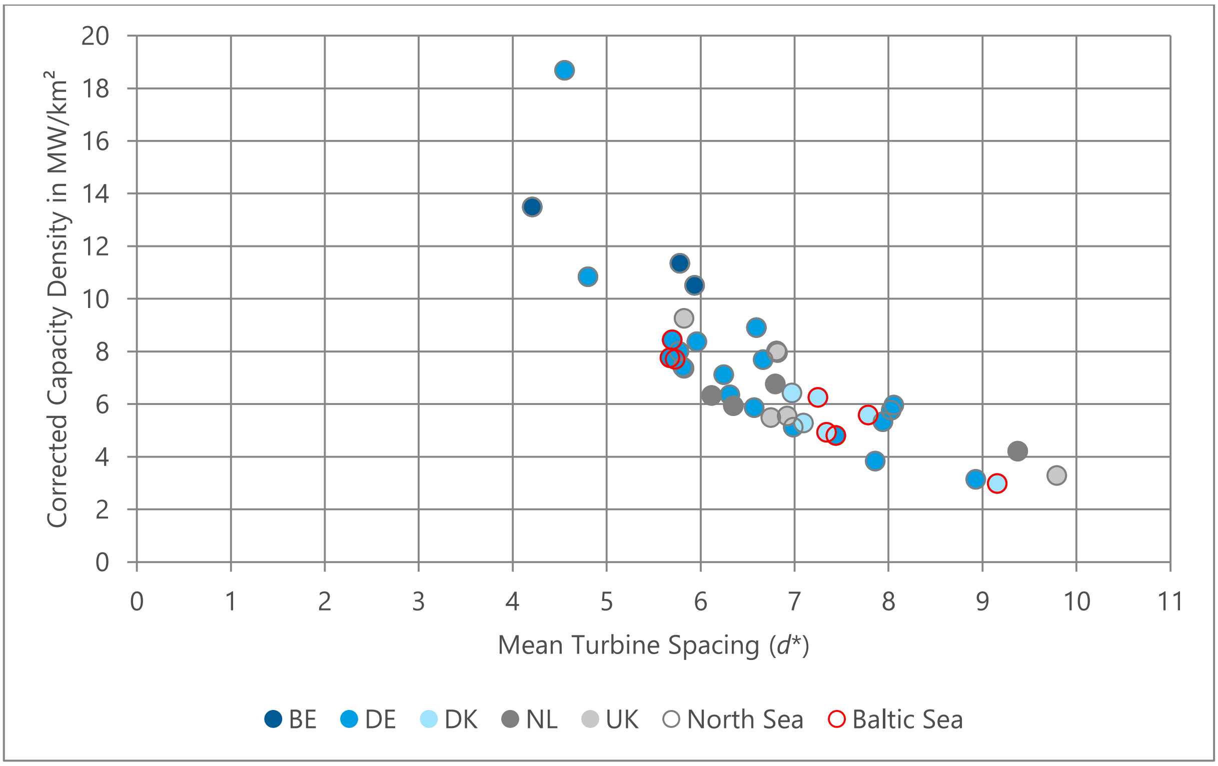


Figure 11:
Corrected capacity density as a function of mean turbine spacing

The analysis shows that wind turbines are not always distributed equally across the wind farm area. Often, a higher number of turbines is placed on the edge of wind farm (see e.g. *Nordsee Ost* (DE, North Sea), *Anholt* (DK, Baltic Sea), *Veja Mate* (DE, North Sea) in the Appendix).

The first offshore wind farms mostly had a line layout (e.g. *Middelgrunden* (DK, North Sea), *Samsø* (DK, North Sea)) or a regular grid layout (e.g. *Belwind* (BE, North Sea), *Alpha Ventus* (DE, North Sea), *Horns Rev 1* (DE, North Sea)). Recent wind farms are often characterized by further optimization that can result in a more erratic layout (see e.g. *Nordsee One* (DE, North Sea), *Gode Wind 1 + 2* (DE, North Sea), *Anholt* (DK, Baltic Sea) in the Appendix).

5 CONCLUSION

Literature assumptions for state-of-the-art and prospective capacity densities for European wind farms range from 5.0 MW/km^2 to 5.4 MW/km^2. These assumptions have mainly been made for the purpose of offshore wind energy potential estimations. For this purpose average values are sufficient. Consequently, the analyzed studies do not reflect on the capacity density variance that can be observed for realized wind farms.

National regulatory frameworks can have a strong impact on the average capacity density of a country's offshore wind farms. If a regulation's primary focus is on a high energy production per sea area, average capacity is likely to be high. This is the case for Belgium, where offshore space is scarce. Therefore regulatory authorities have obliged wind farm developers to use the given area as intensively as possible. On the contrary, if the focus is on the minimization of electricity cost, average capacity density is likely to be low. This is the case for Denmark and the United Kingdom that have extensive offshore space resources.

Nominal capacity density is determined as the ratio of wind farm capacity and wind farm area, calculated from a closed polygon connecting the wind turbines on the wind farm's edges. This area does not provide sufficient space around the outer wind turbines to allow for scalability of the wind farm. Also, the capacity density of wind farms is being overestimated, especially for wind farms with only few turbines. Therefore, a corrected capacity density has to be calculated that allows for scalability and comparability.

A better understanding of project specific reasons for the choice of capacity density could be gained through project developer interviews.

The analysis of realized offshore wind farms in Europe shows that average corrected capacity densities for the analyzed wind farms in the North Sea region (6.0 MW/km²) and the Baltic Sea region (5.5 MW/km²) are close to the literature assumptions. Still, corrected capacity densities vary significantly between countries and wind farms in a range from 3.1 MW/km² (DanTysk, DE, North Sea) to 18.7 MW/km² (Nordergünde, DE, North Sea). This is because a project developer's choice of capacity density depends on many influences next to a country's regulatory framework, such as the availability and accessibility of offshore space, environmental and other restrictions, the project's cost and compensation structure, the developer's expectations on the return on investment and on future electricity prices, or the site's wind conditions. A detailed analysis of these project specifics could be the objective of further investigations, for instance by conducting interviews with project developers.

The difference in the average capacity densities of the North Sea region and the Baltic Sea region can be partly explained by the strong influence of national regulatory frameworks. Another reason might be lower specific power ratings as a consequence of the slightly lower wind speeds in the Baltic Sea.

For the analyzed wind farms, turbine spacing shows to be the dominant driver of capacity density. That means, wind farms with high capacity densities are characterized by low distances between wind turbines.

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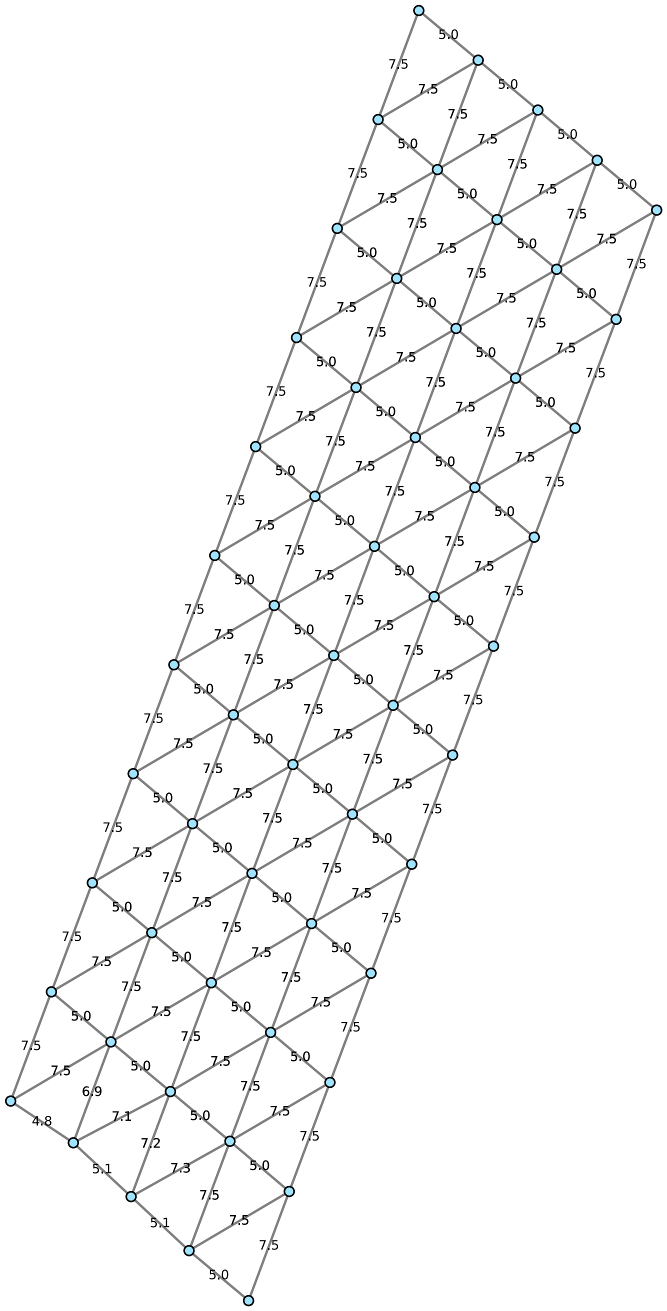
APPENDIX

WIND FARMS

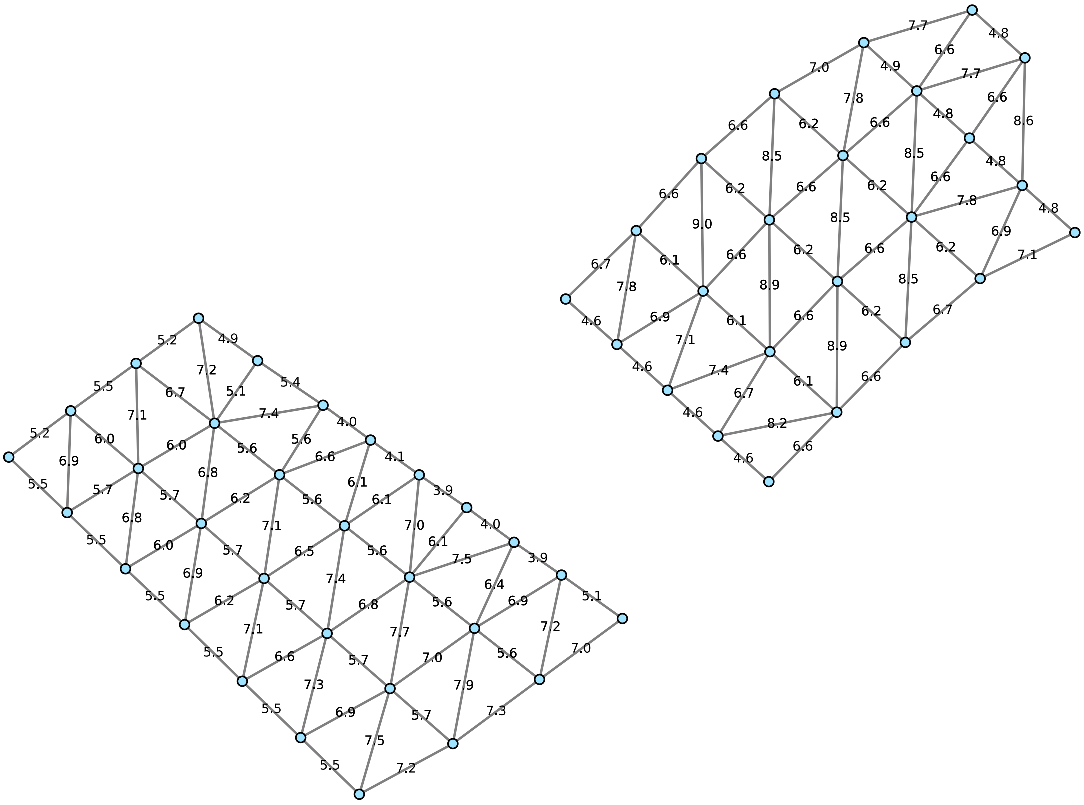
The following figures show an analysis of windfarms, which are already online or will go online soon. Distances between adjacent wind turbines are given in rotor diameters. Average rotor diameters and turbine ratings are used for wind farms with more than one turbine type. The wind farms are sorted by country and year of commissioning.

BE, BELWIND



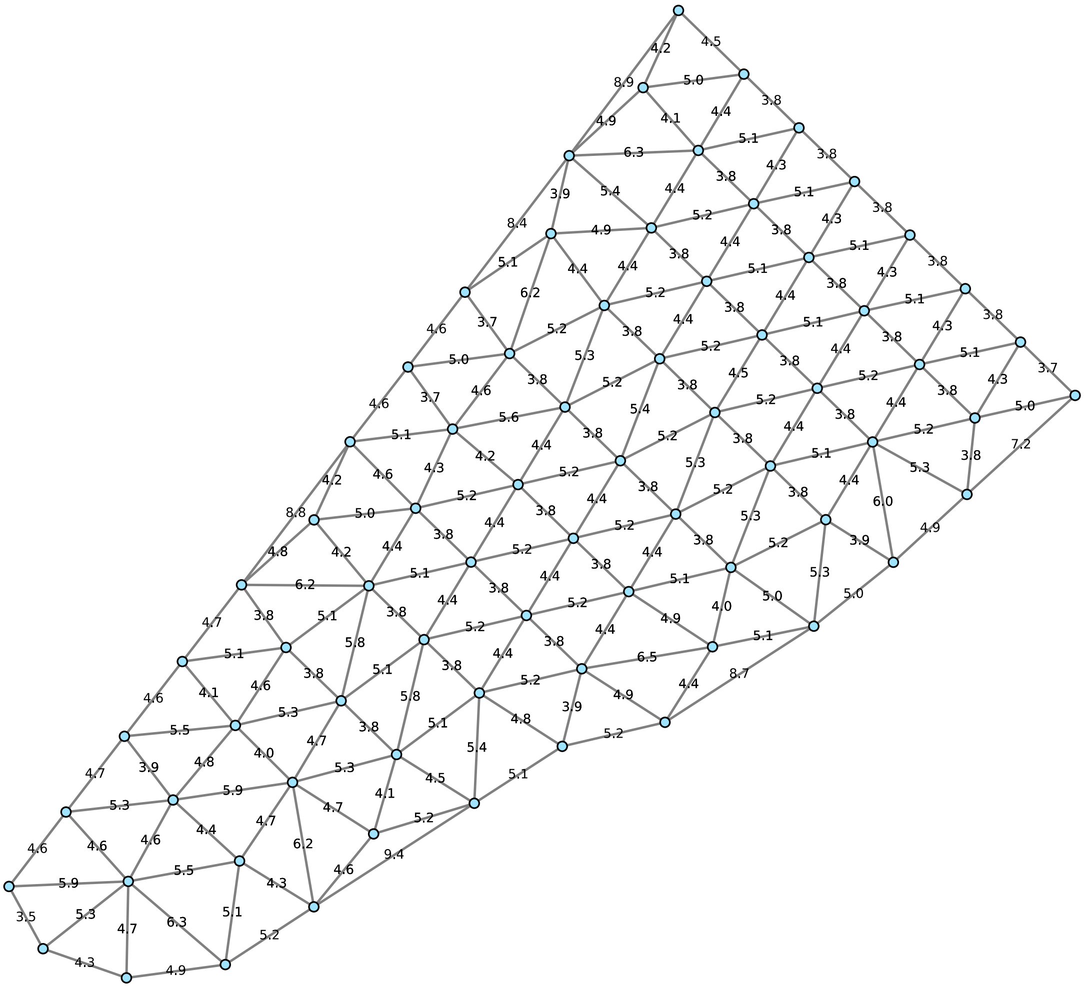
BE, North Sea, Belwind, 2010
55 x Vestas V90-3.0 MW
sources: FOD Economie, 4C Offshore
$H = 72.0$ m, $D = 90.0$ m, $P_{rated,T} = 3.0$ MW, $p_{A_{rotor}} = 471.6$ W/m^2
$A_{WF} = 11.4$ km^2, $P_{WF} = 165.0$ MW, $p_{A_{WF}} = 14.4$ MW/km^2, $p_{A_{WF}}* = 10.5$ MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 7.8$, $d_{\perp} = 5.0$, $d* = 5.9$

BE, THORNTON BANK



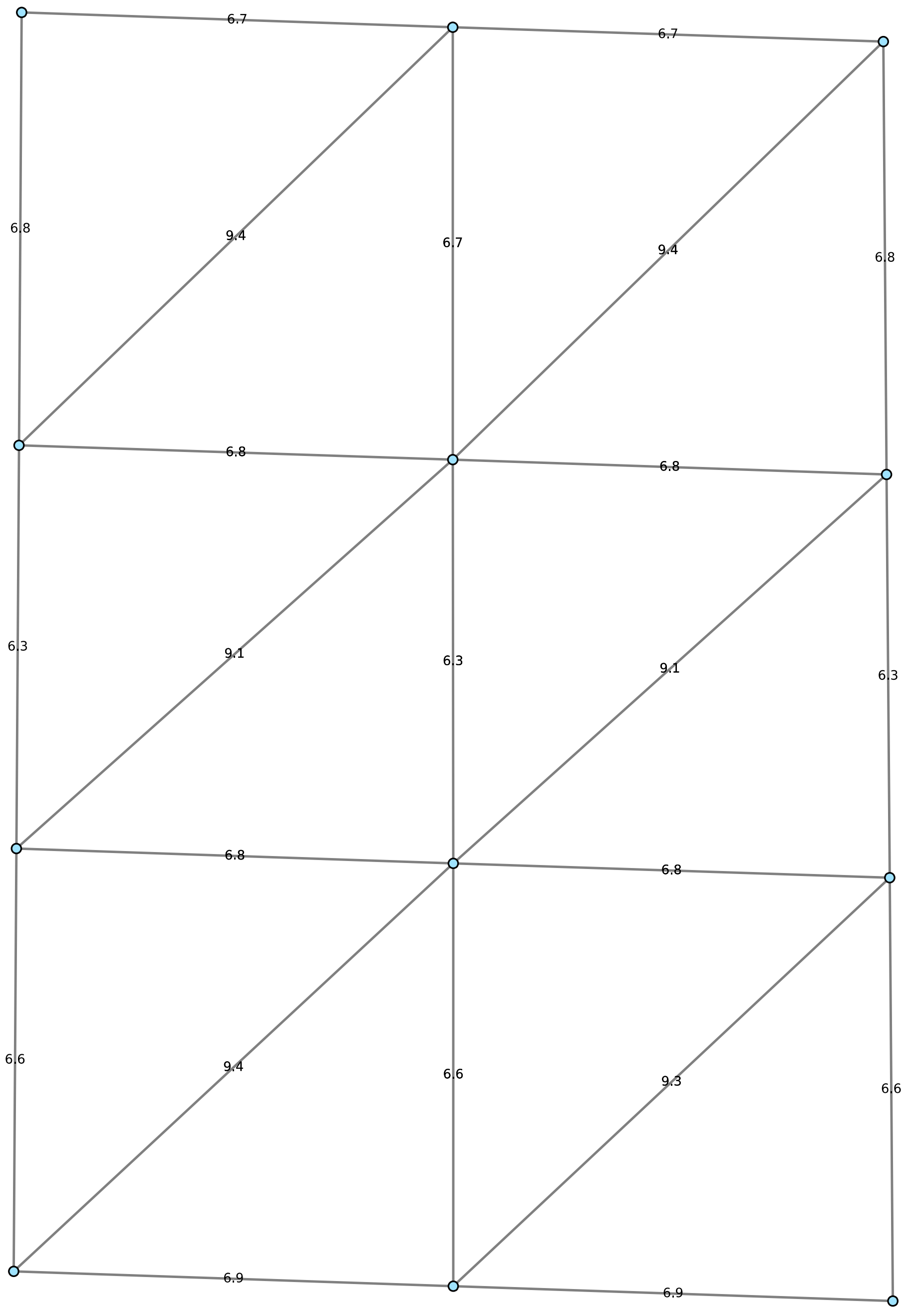
BE, North Sea, Thornton Bank, 2013
54 x Senvion 5M126, Senvion 6.2M126
sources: FOD Economie, 4C Offshore
$H = 95.0$ m, $D = 126.0$ m, $P_{rated,T} = 6.02$ MW, $p_{A_{rotor}} = 483.0$ W/m^2
$A_{WF} = 18.6$ km^2, $P_{WF} = 325.2$ MW, $p_{A_{WF}} = 17.5$ MW/km^2, $p_{A_{WF}}* = 11.3$ MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 6.7$, $d_{\perp} = 5.3$, $d* = 5.8$

BE, NORTHWIND



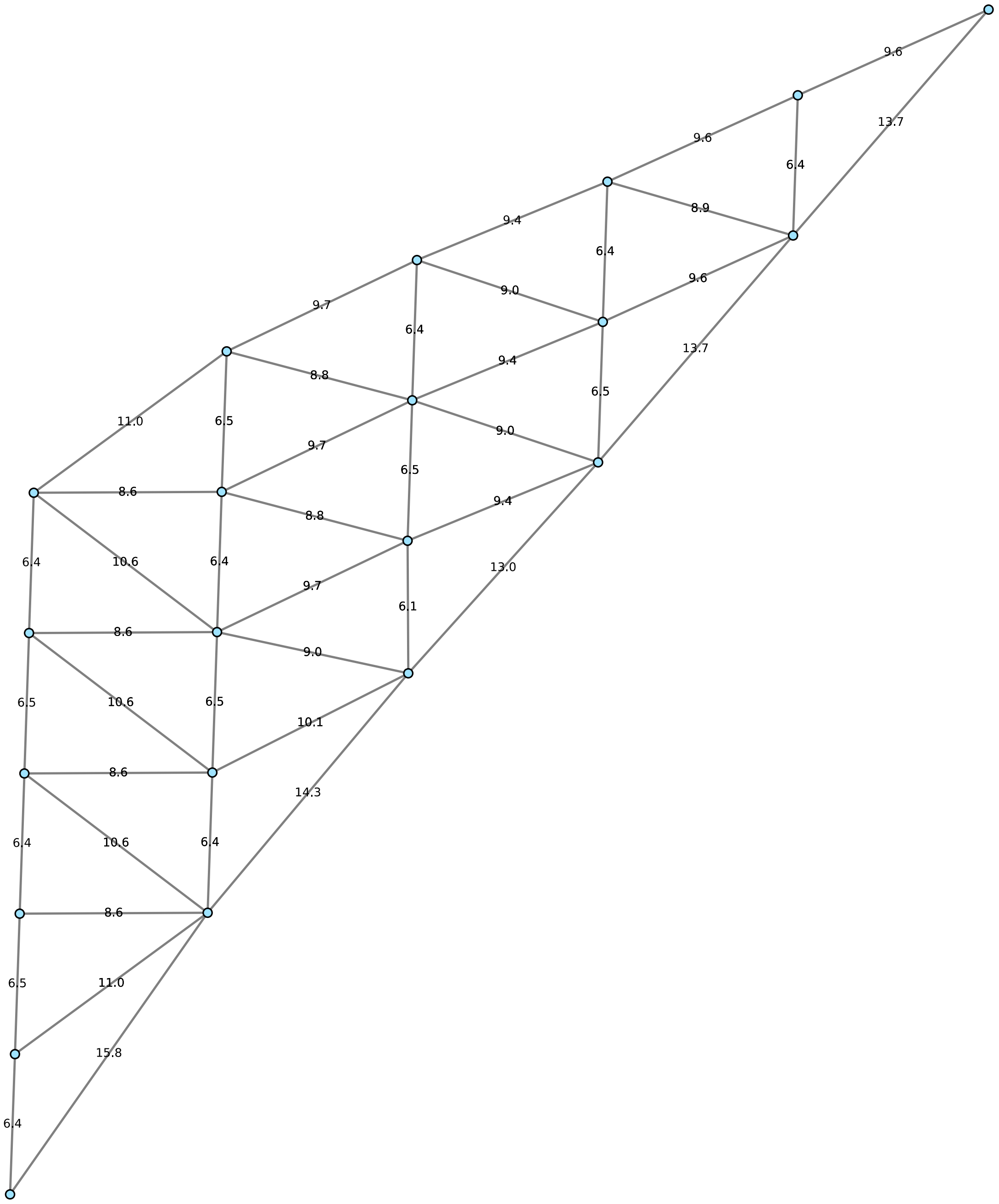
BE, North Sea, Northwind, 2014
72 x Vestas V112-3.0 MW
sources: FOD Economie, 4C Offshore
$H = 71.0$ m, $D = 112.0$ m, $P_{rated,T} = 3.0$ MW, $p_{A_{rotor}} = 304.5$ W/m^2
$A_{WF} = 12.8$ km^2, $P_{WF} = 216.0$ MW, $p_{A_{WF}} =$ 16.9 MW/km^2, $p_{A_{WF}}* =$ 13.5 MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 4.6$, $d_{\perp} = 3.7$, $d* = 4.2$

DE, ALPHA VENTUS



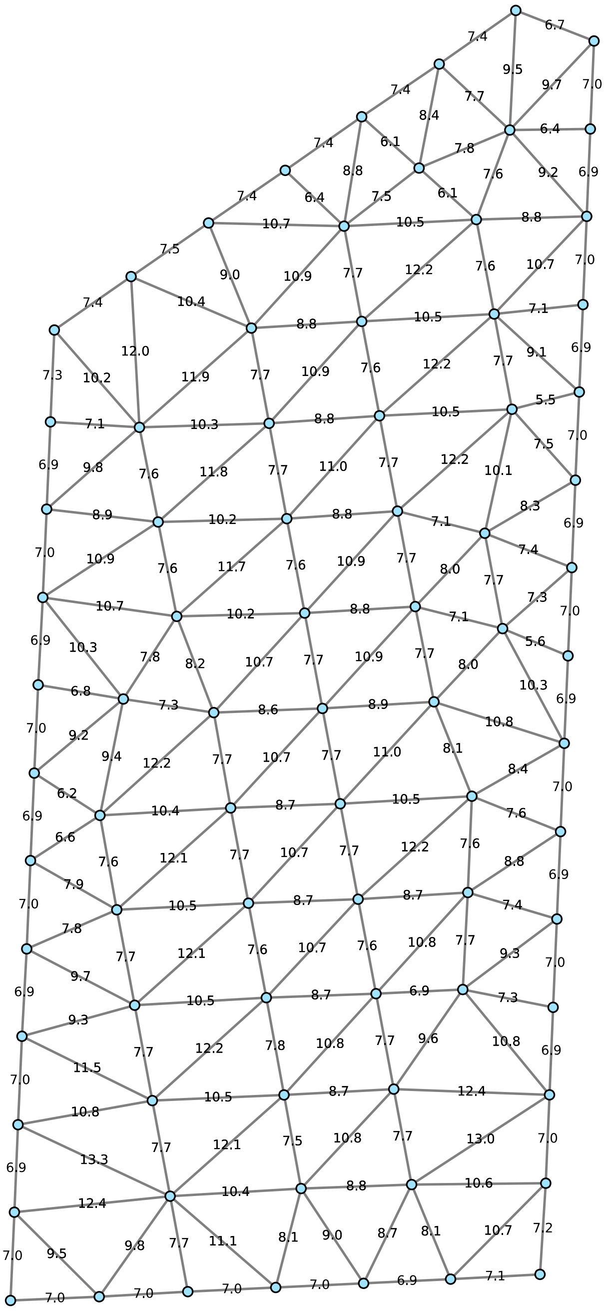
DE, North Sea, Alpha Ventus, 2010
12 x Senvion 5M126 / Areva M5000-116
sources: OSM, 4C Offshore
$H = 92.0$ m, $D = 121.0$ m, $P_{rated,T} = 5.0$ MW, $p_{A_{rotor}} = 434.8$ W/m^2
$A_{WF} = 3.9$ km^2, $P_{WF} = 60.0$ MW, $p_{A_{WF}} =$ 15.4 MW/km^2, $p_{A_{WF}}* =$ 7.7 MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 8.7$, $d_{\perp} = 5.5$, $d* = 6.7$

DE, ENBW BALTIC 1



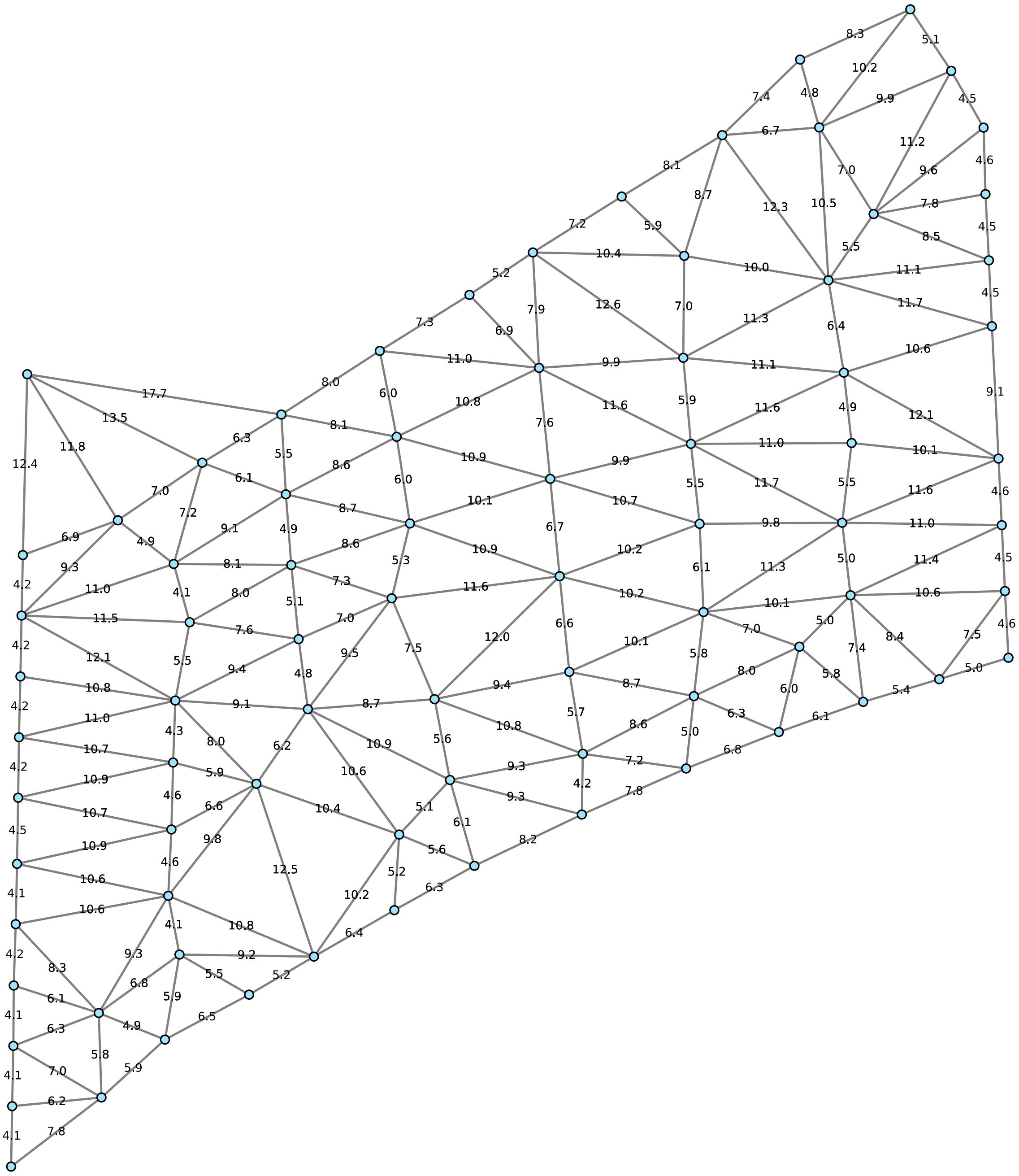
DE, Baltic Sea, Baltic 1, 2011
21 x Siemens SWT-2.3-93
sources: OSM, 4C Offshore
$H = 67.0$ m, $D = 93.0$ m, $P_{rated,T} = 2.3$ MW, $p_{A_{rotor}} = 338.6$ W/m^2
$A_{WF} = 6.0$ km^2, $P_{WF} = 48.3$ MW, $p_{A_{WF}} =$ 8.1 MW/km^2, $p_{A_{WF}}* =$ 4.8 MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 12.1$, $d_{\perp} = 4.8$, $d* = 7.4$

DE, BARD OFFSHORE 1



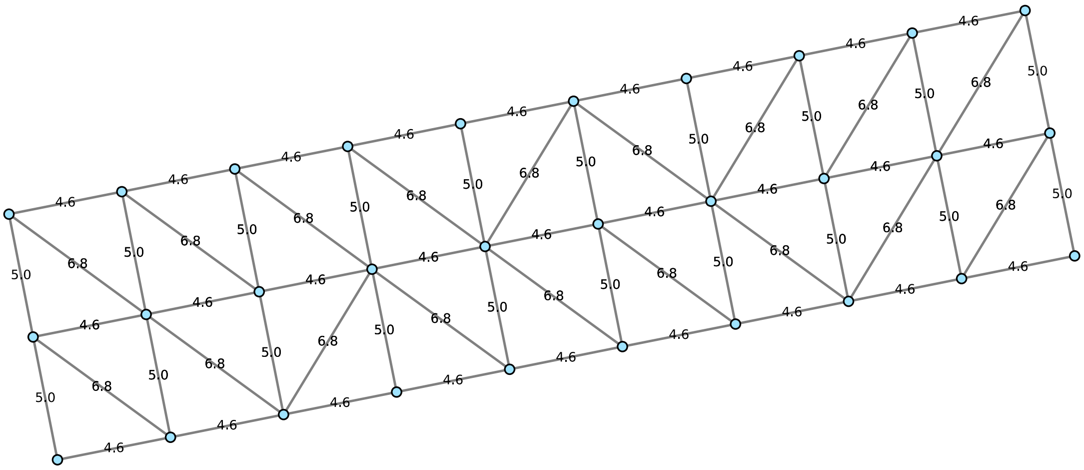
DE, North Sea, Bard Offshore 1, 2013
80 x Bard 5.0
sources: OSM, 4C Offshore
$H = 90.0$ m, $D = 122.0$ m, $P_{rated,T} = 5.0$ MW, $p_{A_{rotor}} = 427.7$ W/m^2
$A_{WF} = 56.3$ km^2, $P_{WF} = 400.0$ MW, $p_{A_{WF}} =$ 7.1 MW/km^2, $p_{A_{WF}}* =$ 5.3 MW/km^2
$\phi = 225.0°$, $d_\parallel = 9.7$, $d_\perp = 6.3$, $d* = 7.9$

DE, MEERWIND SÜD/OST 1



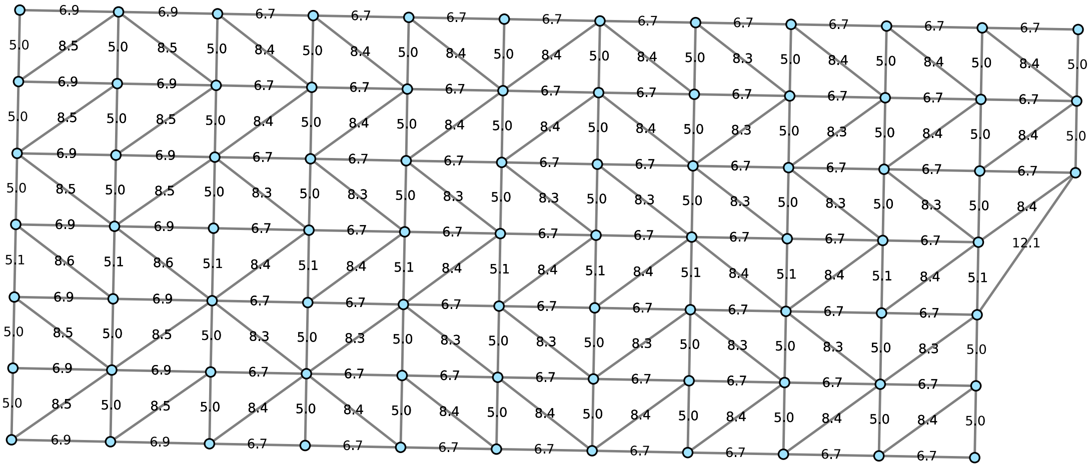
DE, North Sea, Meerwind Süd/Ost, 2014
80 x Siemens SWT-3.6-120
sources: BSH, 4C Offshore
$H = 89.0$ m, $D = 120.0$ m, $P_{rated,T} = 3.6$ MW, $p_{A_{rotor}} = 318.3$ W/m^2
$A_{WF} = 41.1$ km^2, $P_{WF} = 288.0$ MW, $p_{A_{WF}} =$ 7.0 MW/km^2, $p_{A_{WF}}* =$ 5.1 MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 8.1$, $d_{\perp} = 4.7$, $d* = 7.0$

DE, RIFFGAT



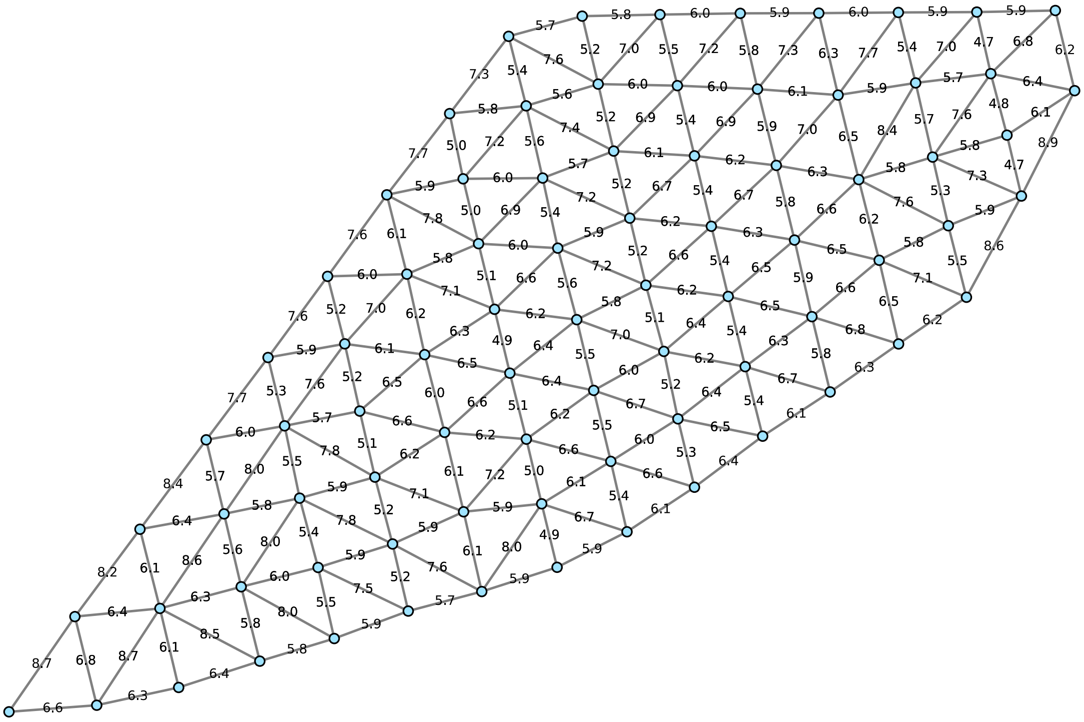
DE, North Sea, Riffgat, 2014
30 x Siemens SWT-3.6-120
sources: OSM, 4C Offshore
$H = 90.0$ m, $D = 120.0$ m, $P_{rated,T} = 3.6$ MW, $p_{A_{rotor}} = 318.3$ W/m^2
$A_{WF} = 6.0$ km^2, $P_{WF} = 108.0$ MW, $p_{A_{WF}} =$ 18.1 MW/km^2, $p_{A_{WF}}* =$ 10.8 MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 7.1$, $d_{\perp} = 3.2$, $d* = 4.8$

DE, AMRUMBANK WEST



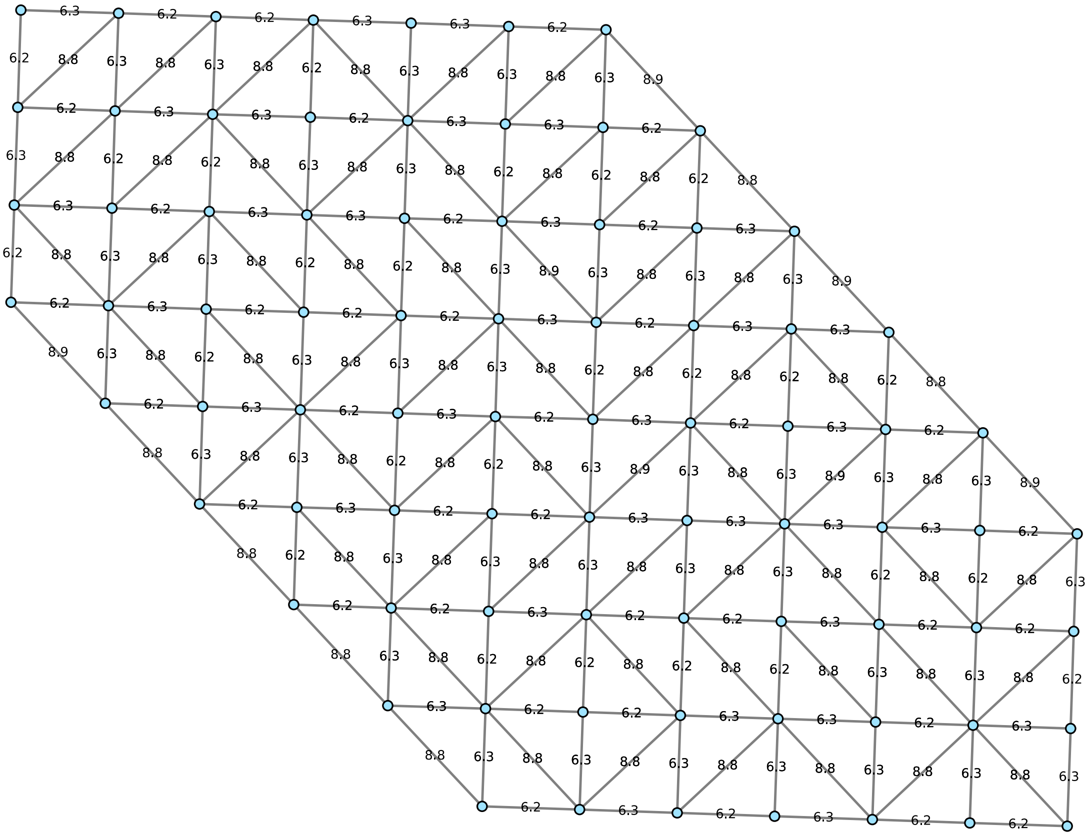
DE, North Sea, Amrumbank West, 2015
80 x Siemens SWT-3.6-120
sources: BSH, 4C Offshore
$H = 90.0$ m, $D = 120.0$ m, $P_{rated,T} = 3.6$ MW, $p_{A_{rotor}} = 318.3$ W/m^2
$A_{WF} = 30.6$ km^2, $P_{WF} = 288.0$ MW, $p_{A_{WF}} =$ 9.4 MW/km^2, $p_{A_{WF}}* =$ 7.4 MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 8.8$, $d_{\perp} = 3.8$, $d* = 5.8$

DE, ENBW BALTIC 2



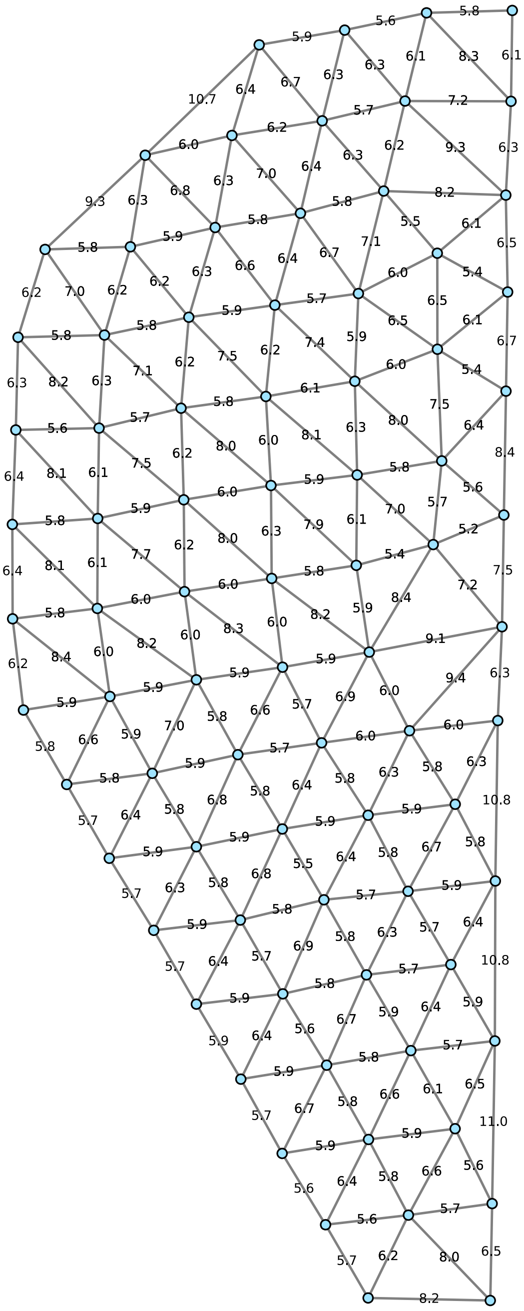
DE, Baltic Sea, Baltic 2, 2015
80 x Siemens SWT-3.6-120
sources: BSH, 4C Offshore
$H = 78.2$ m, $D = 120.0$ m, $P_{rated,T} = 3.6$ MW, $p_{A_{rotor}} = 318.3$ W/m^2
$A_{WF} = 29.5$ km^2, $P_{WF} = 288.0$ MW, $p_{A_{WF}} = 9.8$ MW/km^2, $p_{A_{WF}}* = 7.8$ MW/km^2
$\phi = 225.0°$, $d_\parallel = 6.5$, $d_\perp = 5.0$, $d* = 5.7$

DE, BORKUM RIFFGRUND 1



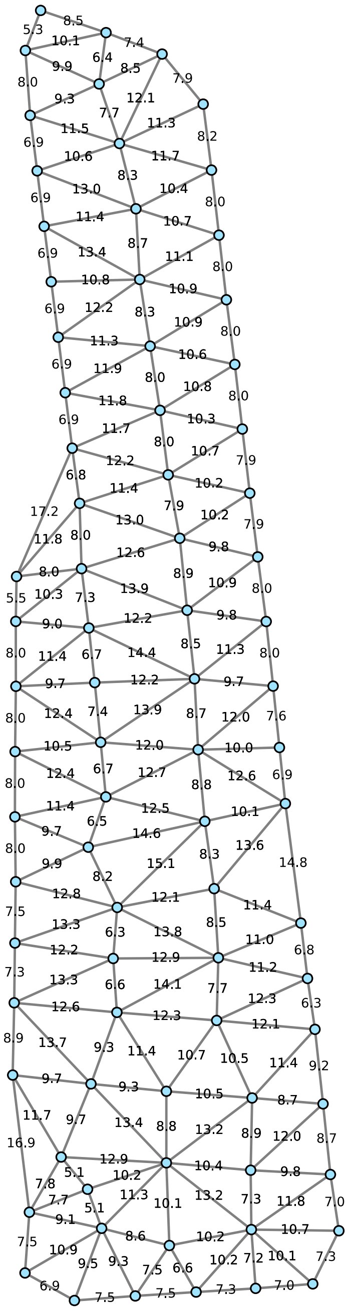
DE, North Sea, Borkum Riffgrund 1, 2015
78 x Siemens SWT-4.0-120
sources: BNetzA, 4C Offshore
$D = 120.0$ m, $P_{rated,T} = 4.0$ MW, $p_{A_{rotor}} = 353.7$ W/m^2
$A_{WF} = 35.4$ km^2, $P_{WF} = 312.0$ MW, $p_{A_{WF}} =$ 8.8 MW/km^2, $p_{A_{WF}}* =$ 7.1 MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 7.7$, $d_{\perp} = 5.5$, $d* = 6.3$

DE, BUTENDIEK



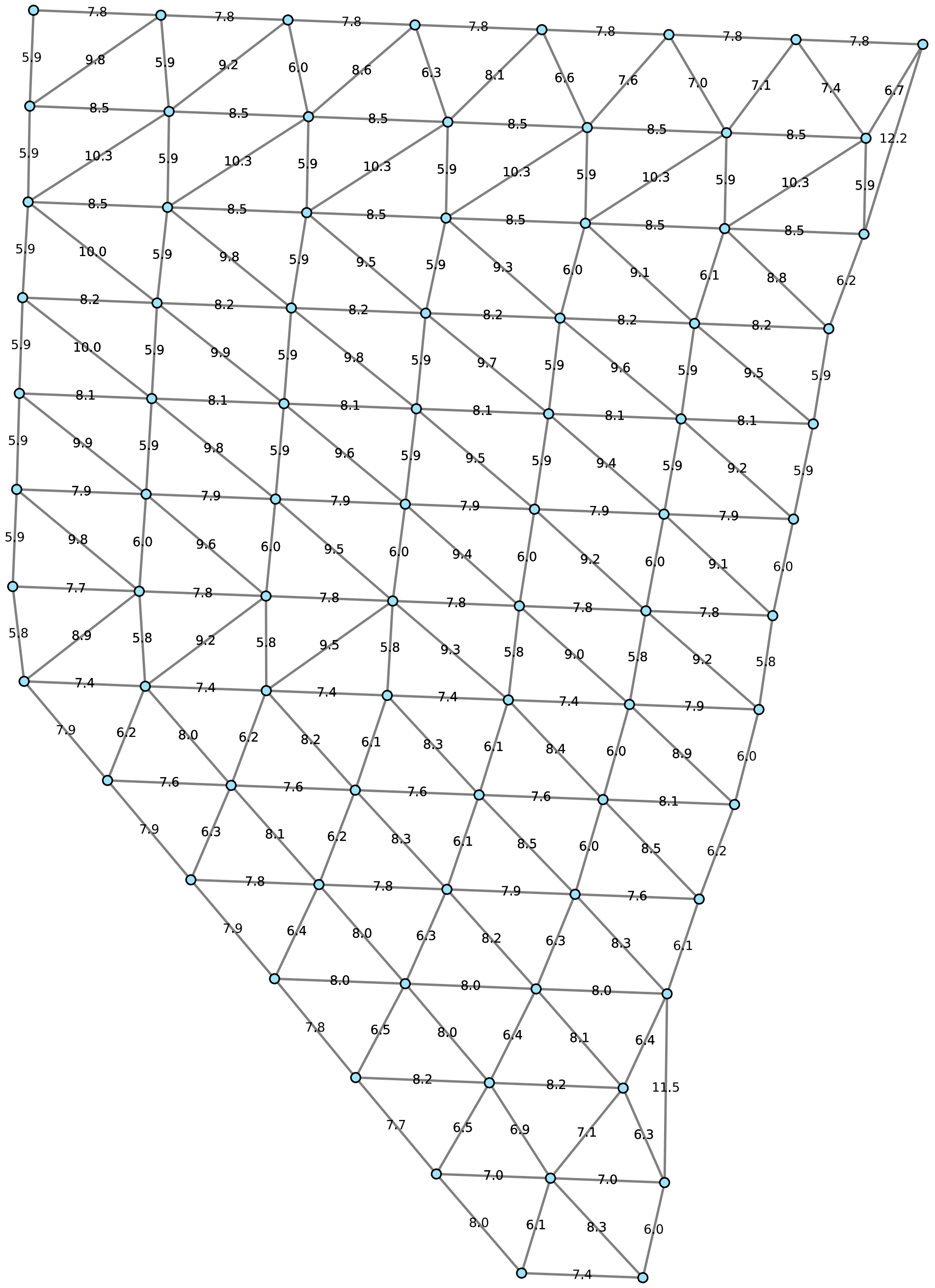
DE, North Sea, Butendiek, 2015
80 x Siemens SWT-3.6-120
sources: BNetzA, 4C Offshore
$H = 90.0$ m, $D = 120.0$ m, $P_{rated,T} = 3.6$ MW, $p_{A_{rotor}} = 318.3$ W/m^2
$A_{WF} = 31.3$ km^2, $P_{WF} = 288.0$ MW, $p_{A_{WF}} = 9.2$ MW/km^2, $p_{A_{WF}}* = 7.4$ MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 7.1$, $d_{\perp} = 5.0$, $d* = 5.8$

DE, DANTYSK



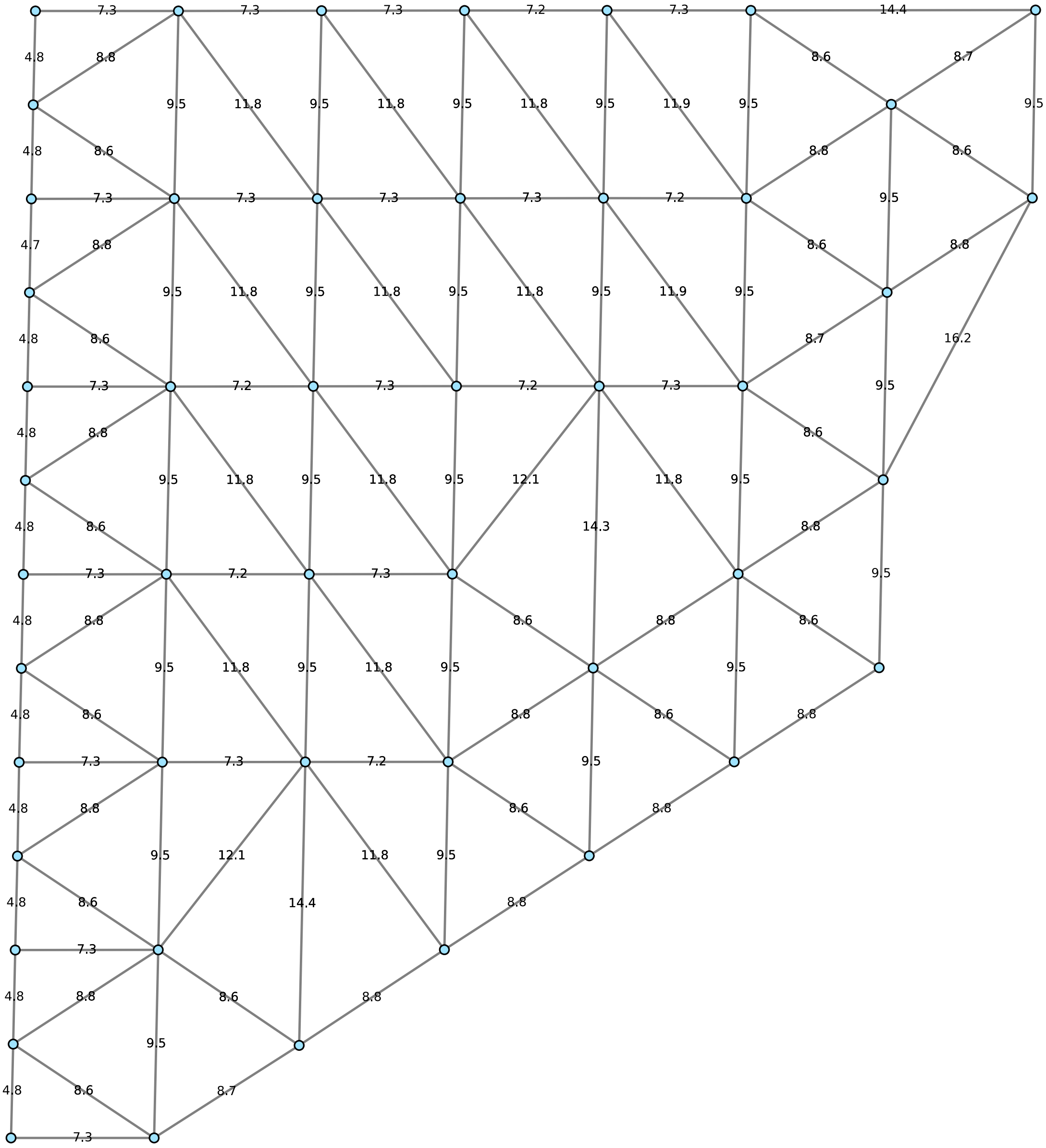
DE, North Sea, DanTysk, 2015
80 x Siemens SWT-3.6-120
sources: BNetzA, 4C Offshore
$H = 88.0$ m, $D = 120.0$ m, $P_{rated,T} = 3.6$ MW, $p_{A_{rotor}} = 318.3$ W/m^2
$A_{WF} = 64.9$ km^2, $P_{WF} = 288.0$ MW, $p_{A_{WF}} = 4.4$ MW/km^2, $p_{A_{WF}}* = 3.1$ MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 11.1$, $d_{\perp} = 6.5$, $d* = 8.9$

DE, GLOBAL TECH 1



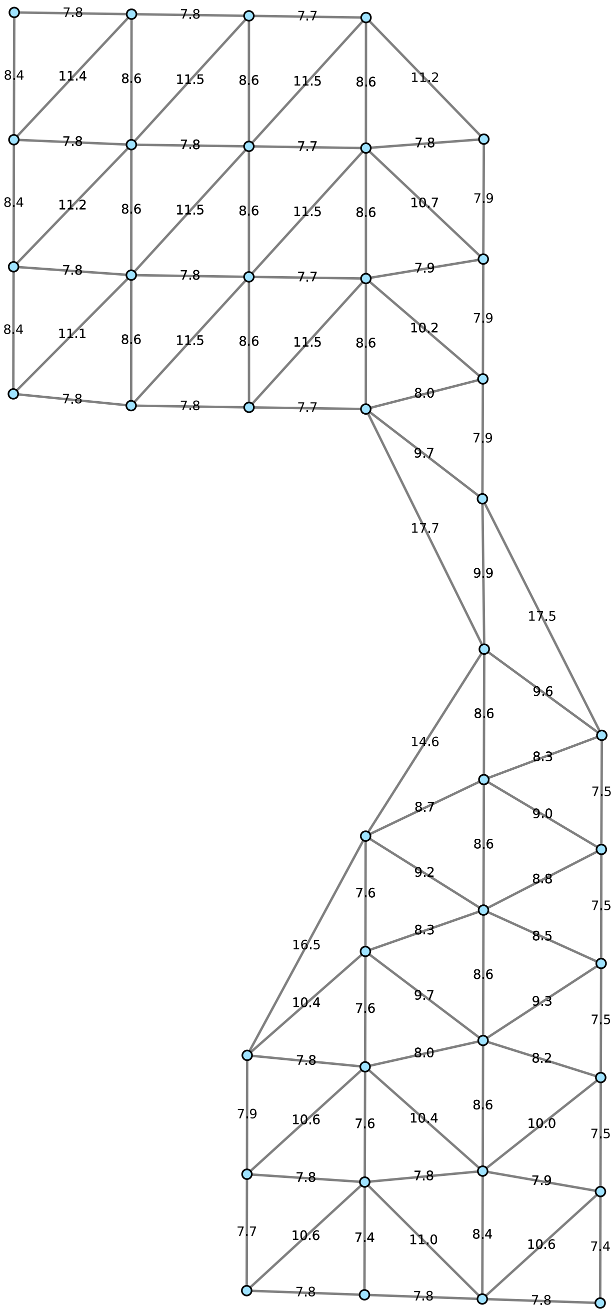
DE, North Sea, Global Tech 1, 2015
80 x Areva M5000-116
sources: BSH, 4C Offshore
$H = 82.0$ m, $D = 116.0$ m, $P_{rated,T} = 5.0$ MW, $p_{A_{rotor}} = 473.1$ W/m^2
$A_{WF} = 39.3$ km^2, $P_{WF} = 400.0$ MW, $p_{A_{WF}} = 10.2$ MW/km^2, $p_{A_{WF}}* = 8.0$ MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 7.3$, $d_{\perp} = 5.1$, $d* = 6.8$

DE, NORDSEE OST



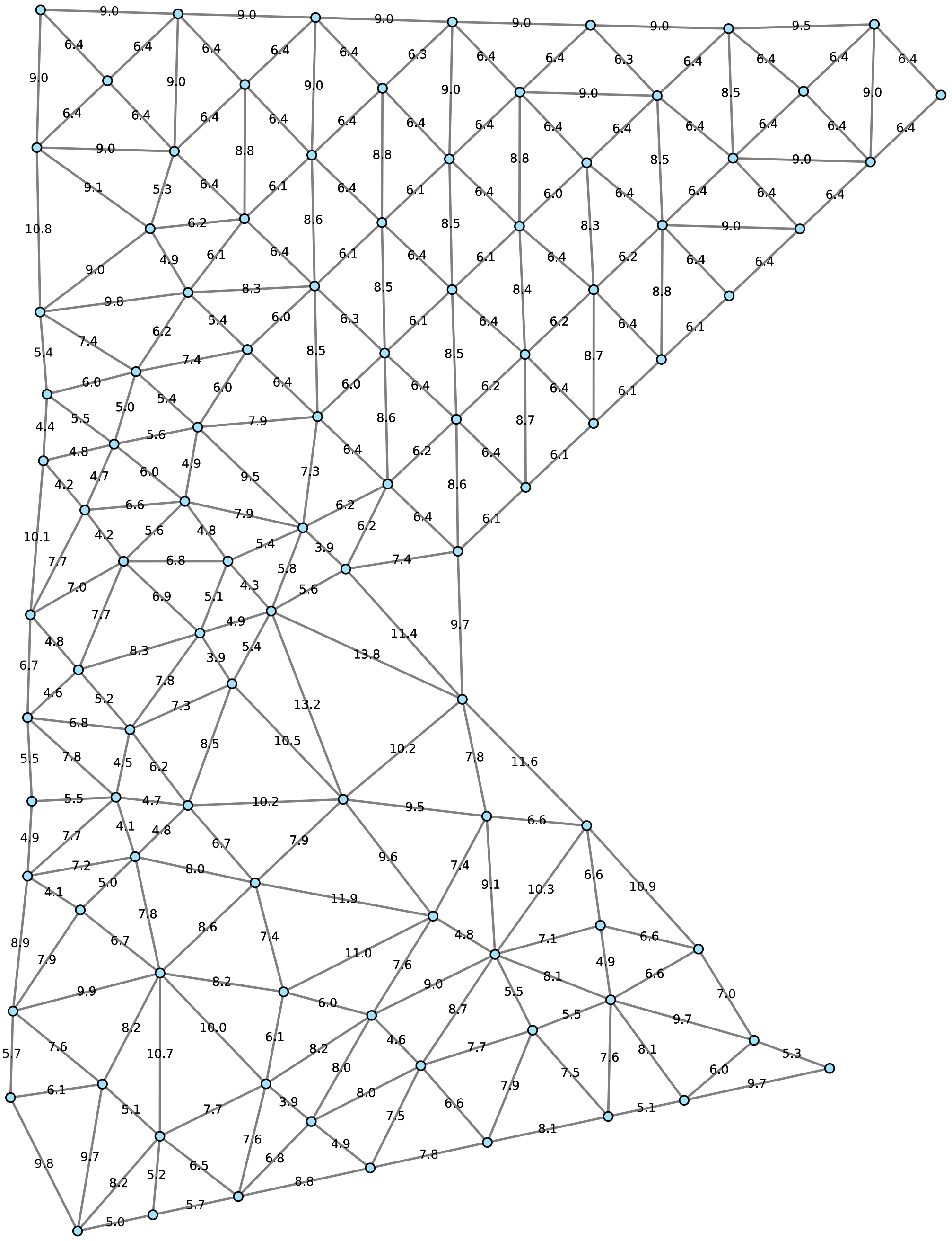
DE, North Sea, Nordsee Ost, 2015
48 x Senvion 6.2M126
sources: BNetzA, 4C Offshore
$H = 92.0$ m, $D = 126.0$ m, $P_{rated,T} = 6.15$ MW, $p_{A_{rotor}} = 493.2$ W/m^2
$A_{WF} = 34.5$ km^2, $P_{WF} = 295.2$ MW, $p_{A_{WF}} = 8.5$ MW/km^2, $p_{A_{WF}}* = 6.0$ MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 9.7$, $d_{\perp} = 6.2$, $d* = 8.1$

DE, TRIANEL WINDPARK BORKUM 1



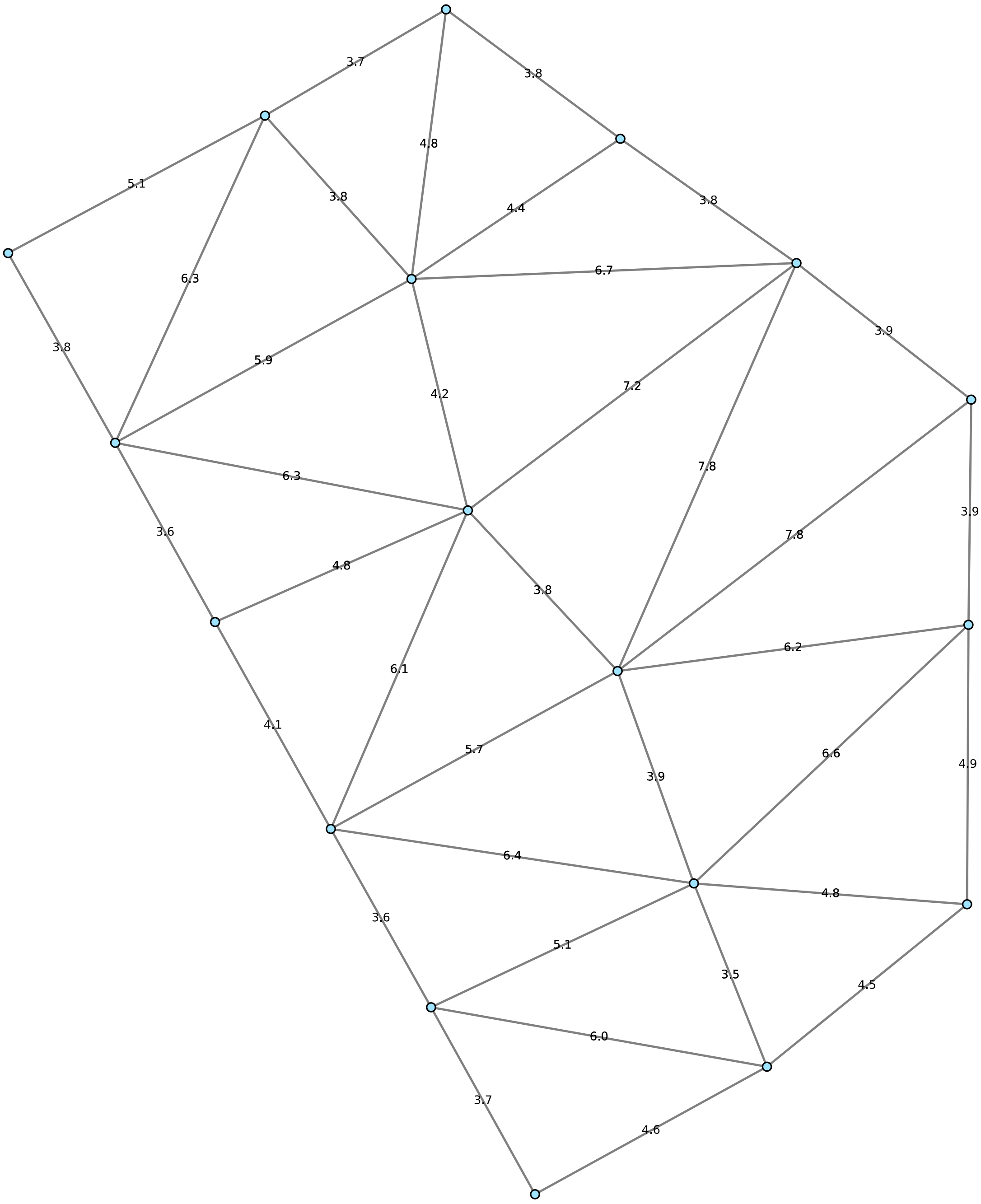
DE, North Sea, Trianel Windpark Borkum 1, 2015
40 x Areva M5000-116
sources: BNetzA, 4C Offshore
$H = 90.0$ m, $D = 116.0$ m, $P_{rated,T} = 5.0$ MW, $p_{A_{rotor}} = 473.1$ W/m^2
$A_{WF} = 22.1$ km^2, $P_{WF} = 200.0$ MW, $p_{A_{WF}} =$ 9.0 MW/km^2, $p_{A_{WF}}* =$ 5.8 MW/km^2
$\phi = 225.0°$, $d_\parallel = 10.3$, $d_\perp = 6.6$, $d* = 8.0$

DE, GODE WIND 1+2



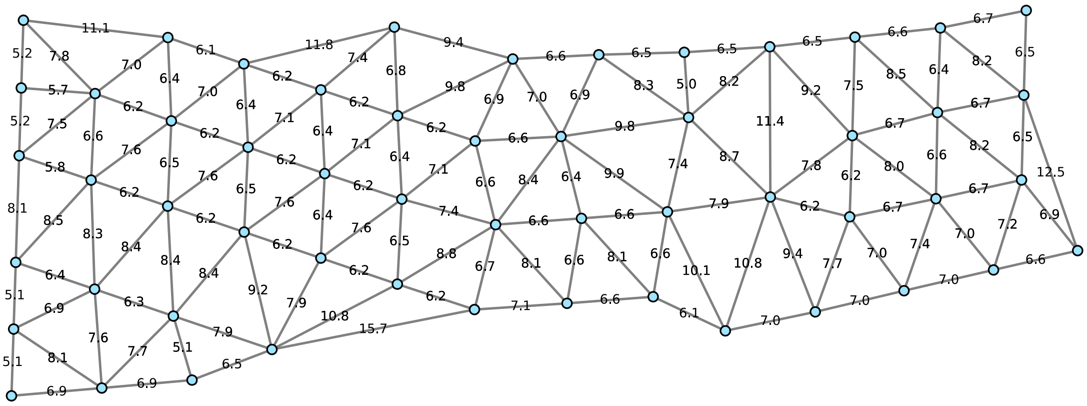
DE, North Sea, Gode Wind 1 + 2, 2017
97 x Siemens SWT-6.0-154
sources: BNetzA, 4C Offshore
$H = 111.0$ m, $D = 154.0$ m, $P_{rated,T} = 6.0$ MW, $p_{A_{rotor}} = 322.1$ W/m^2
$A_{WF} = 73.3$ km^2, $P_{WF} = 582.0$ MW, $p_{A_{WF}} =$ 7.9 MW/km^2, $p_{A_{WF}}* =$ 6.3 MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 6.8$, $d_{\perp} = 4.9$, $d* = 6.3$

DE, NORDERGRÜNDE



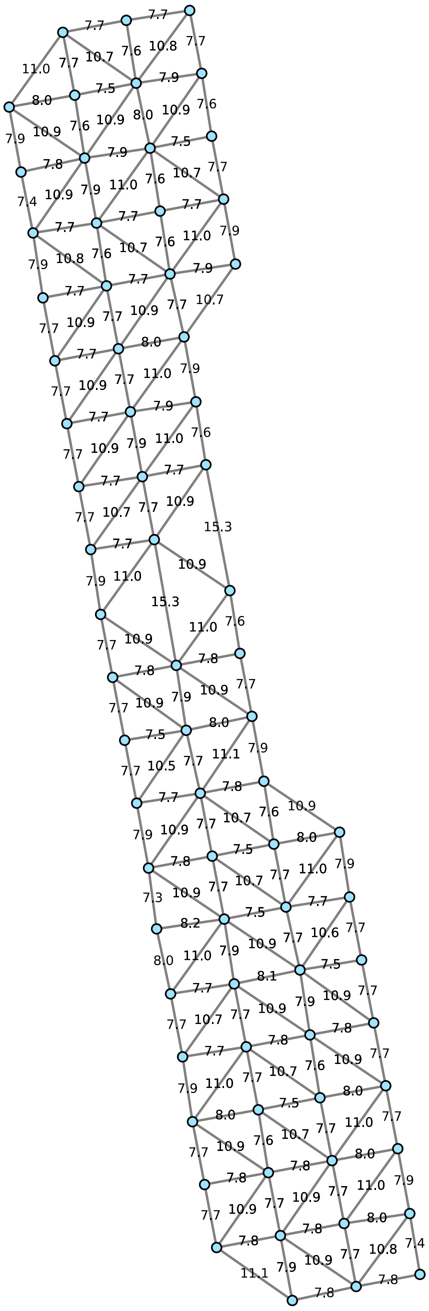
DE, North Sea, Nordergründe, 2017
18 x Senvion 6.2M126
sources: BNetzA, 4C Offshore
$H = 84.0$ m, $D = 126.0$ m, $P_{rated,T} = 6.15$ MW, $p_{A_{rotor}} = 493.2$ W/m^2
$A_{WF} = 3.3$ km^2, $P_{WF} = 110.7$ MW, $p_{A_{WF}} = 33.6$ MW/km^2, $p_{A_{WF}}* = 18.7$ MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 5.3$, $d_{\perp} = 3.6$, $d* = 4.6$

DE, NORDSEE ONE



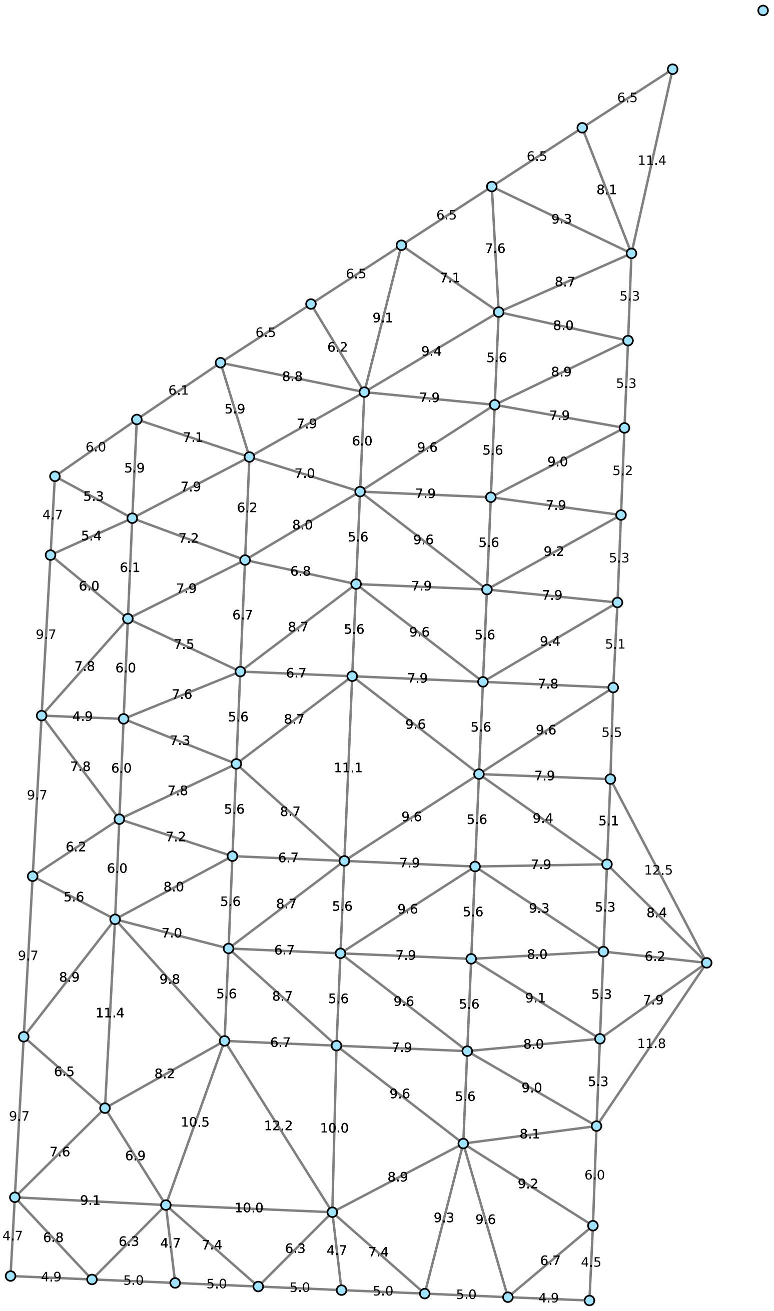
DE, North Sea, Nordsee One, 2017
54 x Senvion 6.2M126
sources: BNetzA, 4C Offshore
$H = 90.0$ m, $D = 126.0$ m, $P_{rated,T} = 6.15$ MW, $p_{A_{rotor}} = 493.2$ W/m^2
$A_{WF} = 26.9$ km^2, $P_{WF} = 332.1$ MW, $p_{A_{WF}} =$ 12.3 MW/km^2, $p_{A_{WF}}* =$ 8.9 MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 7.6$, $d_{\perp} = 5.5$, $d* = 6.6$

DE, SANDBANK



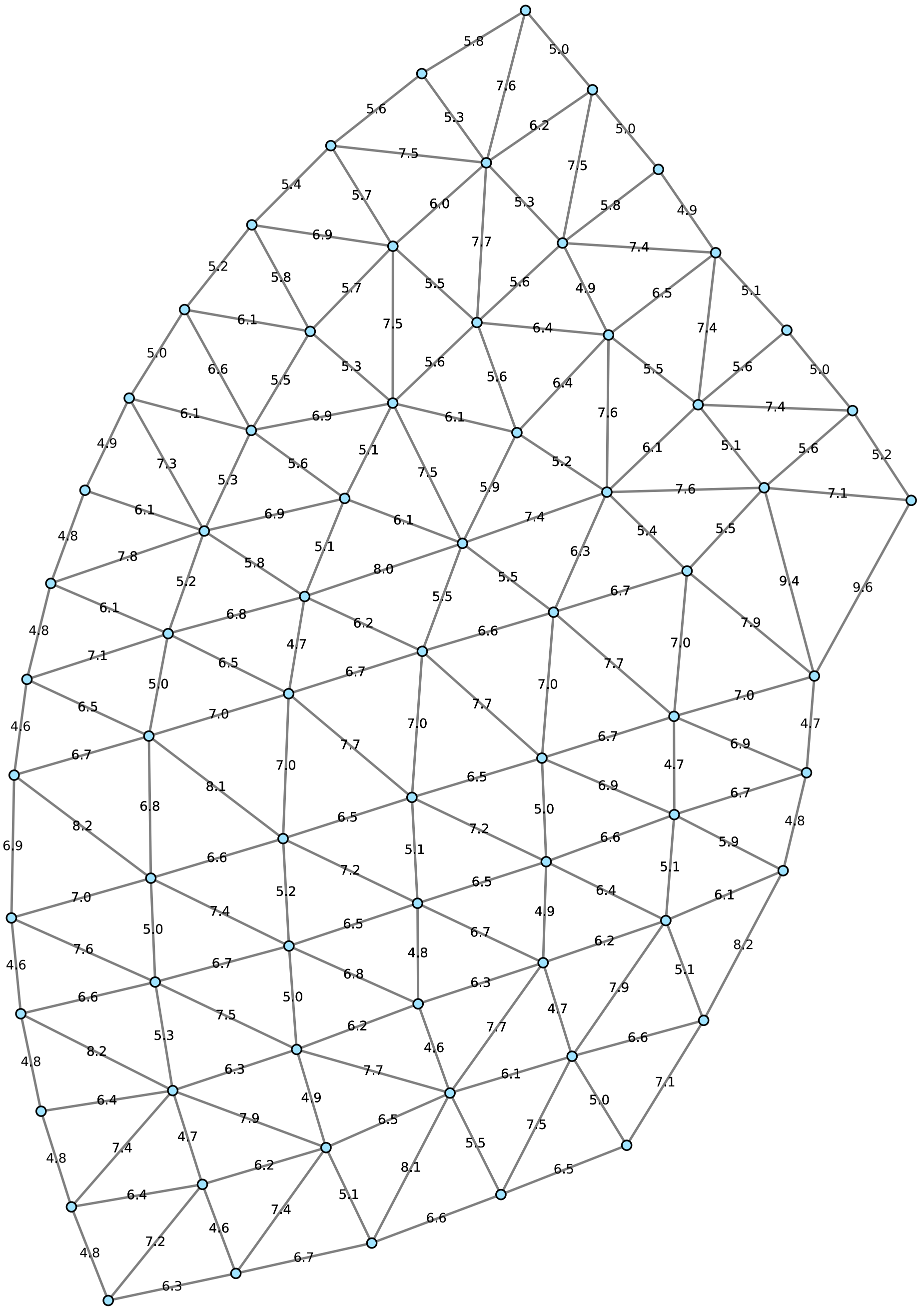
DE, North Sea, Sandbank, 2017
72 x Siemens SWT-4.0-130
sources: BNetzA, 4C Offshore
$H = 94.8$ m, $D = 130.0$ m, $P_{rated,T} = 4.0$ MW, $p_{A_{rotor}} = 301.4$ W/m^2
$A_{WF} = 51.7$ km^2, $P_{WF} = 288.0$ MW, $p_{A_{WF}} =$ 5.6 MW/km^2, $p_{A_{WF}}* =$ 3.8 MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 8.9$, $d_{\perp} = 6.9$, $d* = 7.9$

DE, VEJA MATE



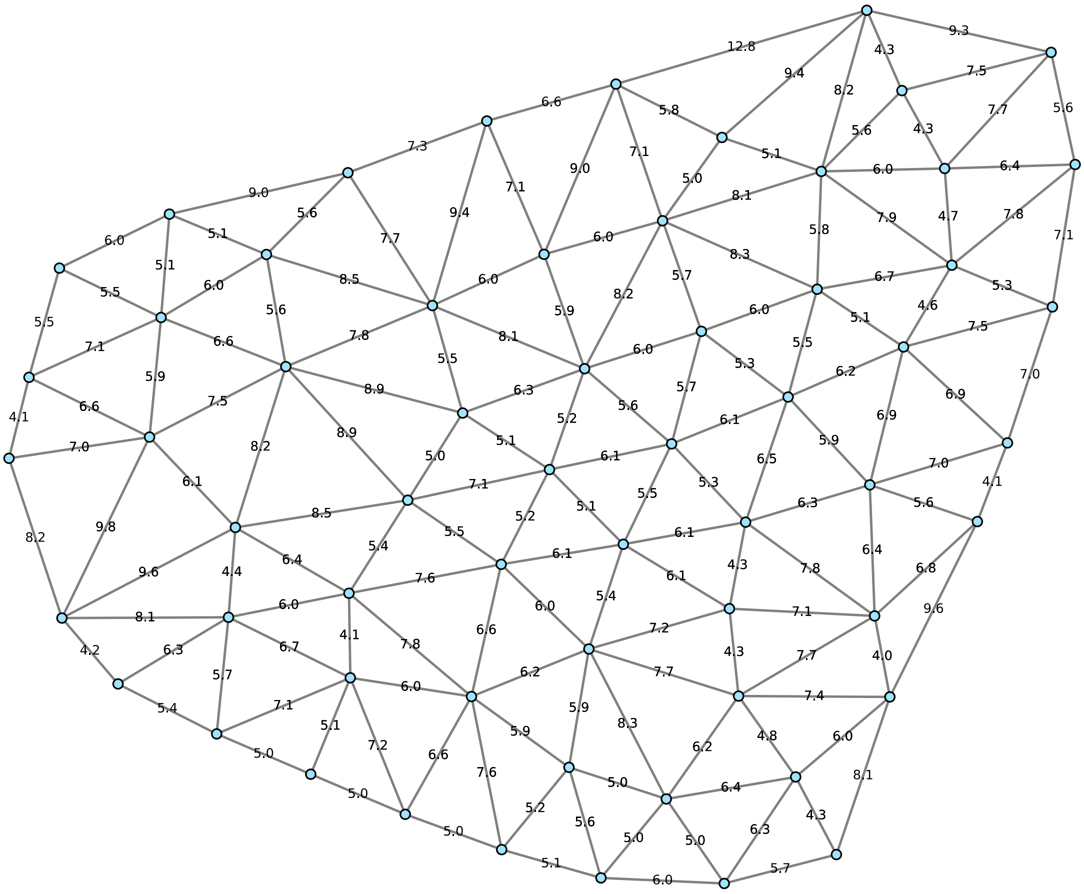
DE, North Sea, Veja Mate, 2017
67 x Siemens SWT-6.0-154
sources: BNetzA, 4C Offshore
$H = 103.3$ m, $D = 154.0$ m, $P_{rated,T} = 6.0$ MW, $p_{A_{rotor}} = 322.1$ W/m^2
$A_{WF} = 51.2$ km^2, $P_{WF} = 402.0$ MW, $p_{A_{WF}} = 7.9$ MW/km^2, $p_{A_{WF}}* = 5.9$ MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 8.1$, $d_{\perp} = 4.6$, $d* = 6.6$

DE, WIKINGER



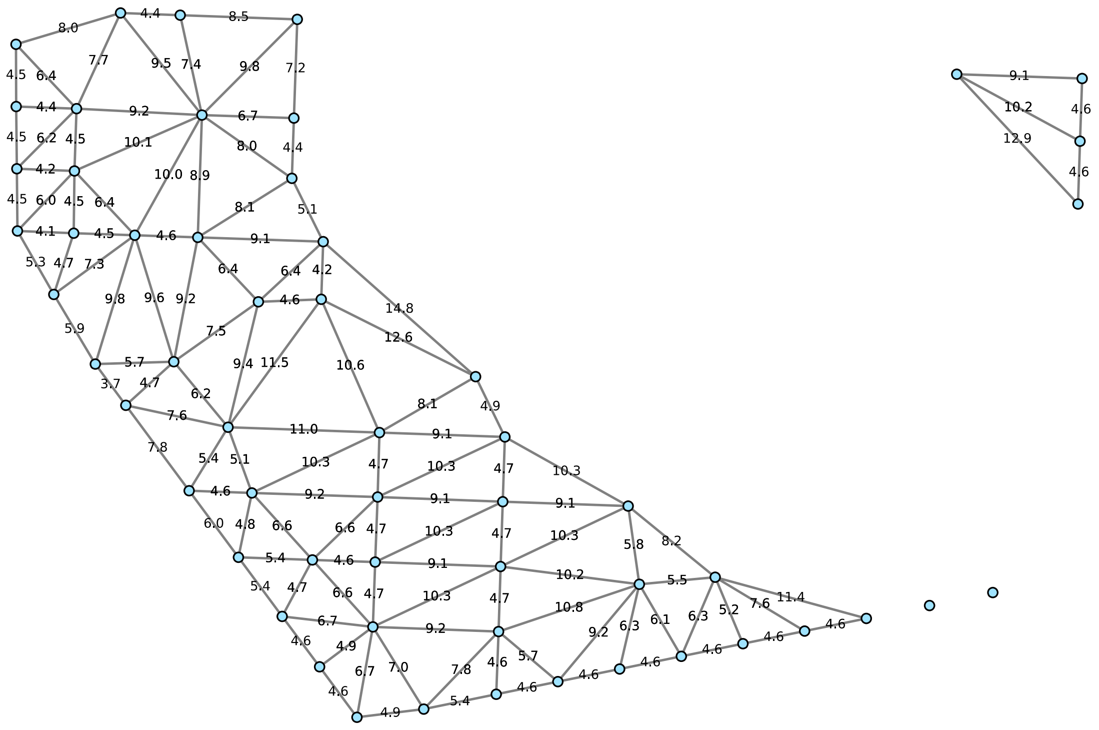
DE, Baltic Sea, Wikinger, 2017
70 x Adwen AD5-135
sources: BNetzA, 4C Offshore
$D = 135.0$ m, $P_{rated,T} = 5.0$ MW, $p_{A_{rotor}} = 349.3$ W/m^2
$A_{WF} = 32.3$ km^2, $P_{WF} = 350.0$ MW, $p_{A_{WF}} =$ 10.8 MW/km^2, $p_{A_{WF}}* =$ 8.4 MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 6.7$, $d_{\perp} = 4.5$, $d* = 5.7$

DE, ARKONA



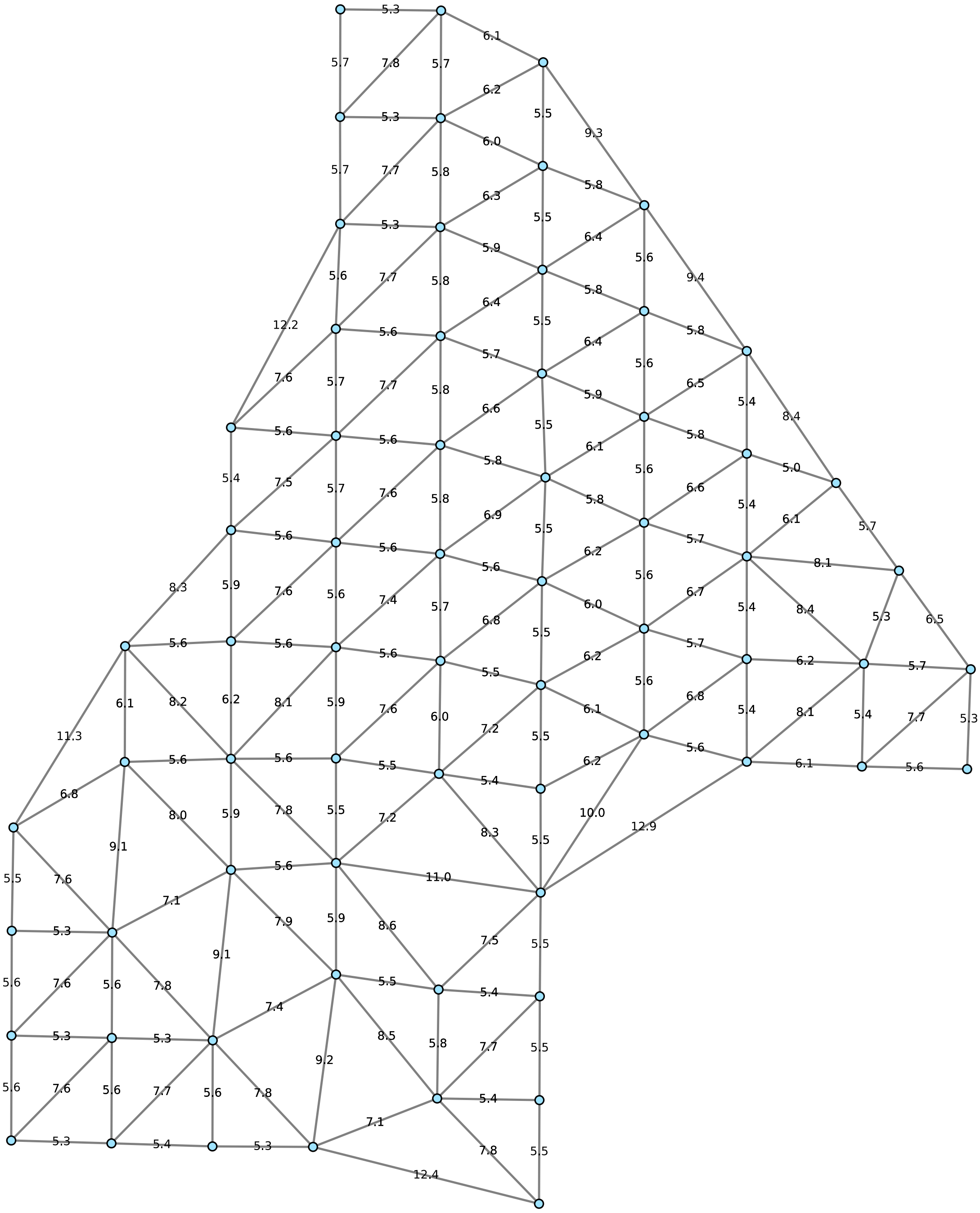
DE, Baltic Sea, Arkona, 2019
60 x Siemens SWT-6.0-154
sources: BSH, 4C Offshore
$H = 102.0$ m, $D = 154.0$ m, $P_{rated,T} = 6.0$ MW, $p_{A_{rotor}} = 322.1$ W/m^2
$A_{WF} = 37.0$ km^2, $P_{WF} = 360.0$ MW, $p_{A_{WF}} =$ 9.7 MW/km^2, $p_{A_{WF}}* =$ 7.7 MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 6.4$, $d_{\perp} = 4.7$, $d* = 5.7$

DE, BORKUM RIFFGRUND 2



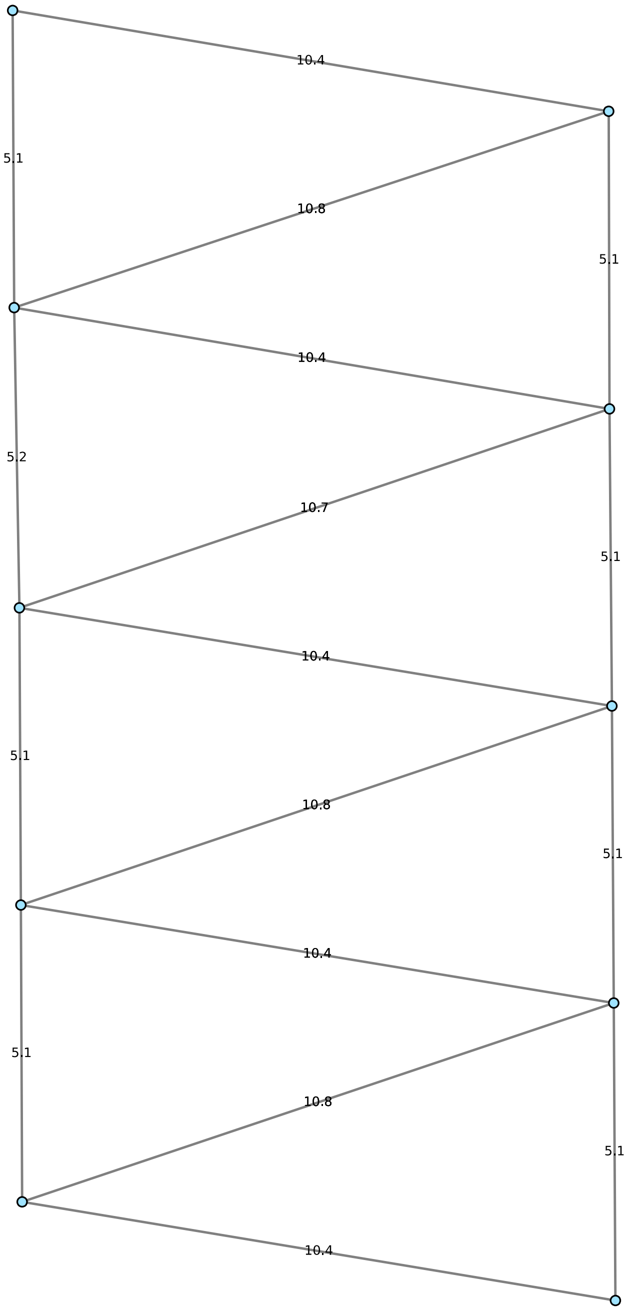
DE, North Sea, Borkum Riffgrund 2, 2019
56 x MHI Vestas V164-8.0 MW
sources: BSH, 4C Offshore
$D = 164.0$ m, $P_{rated,T} = 8.0$ MW, $p_{A_{rotor}} = 378.7$ W/m^2
$A_{WF} = 35.4$ km^2, $P_{WF} = 448.0$ MW, $p_{A_{WF}} =$ 12.7 MW/km^2, $p_{A_{WF}}* =$ 8.4 MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 6.8$, $d_{\perp} = 4.1$, $d* = 6.0$

DE, MERKUR



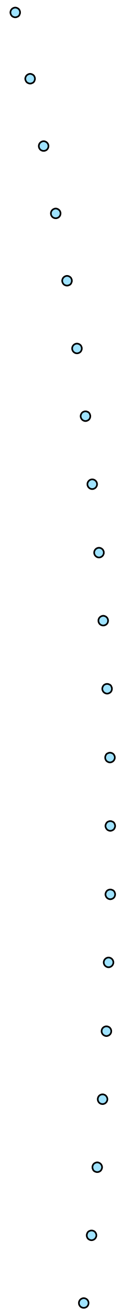
DE, North Sea, Merkur, 2019
66 x GE Haliade 150-6MW
sources: BSH, 4C Offshore
$H = 120.6$ m, $D = 150.0$ m, $P_{rated,T} = 6.0$ MW, $p_{A_{rotor}} = 339.5$ W/m^2
$A_{WF} = 38.6$ km^2, $P_{WF} = 396.0$ MW, $p_{A_{WF}} =$ 10.3 MW/km^2, $p_{A_{WF}}* =$ 8.0 MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 6.9$, $d_{\perp} = 4.8$, $d* = 5.8$

DK, TUNØ KNOB



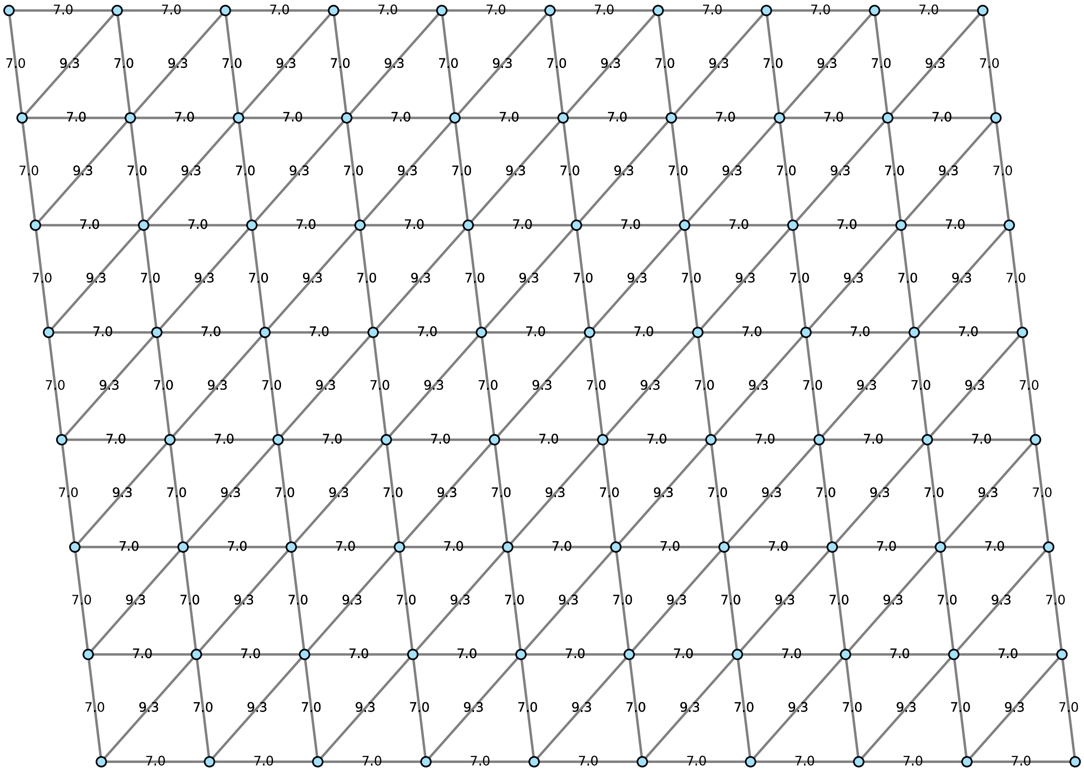
DK, Baltic Sea, Tunø Knob, 1995
10 x Vestas V39-500kW
sources: ENS, 4C Offshore
$H = 45.0$ m, $D = 39.0$ m, $P_{rated,T} = 0.5$ MW, $p_{A_{rotor}} = 418.6$ W/m^2
$A_{WF} = 0.3$ km^2, $P_{WF} = 5.0$ MW, $p_{A_{WF}} = 15.6$ MW/km^2, $p_{A_{WF}}* = 6.3$ MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 6.2$, $d_{\perp} = 4.5$, $d* = 7.3$

DK, MIDDELGRUNDEN



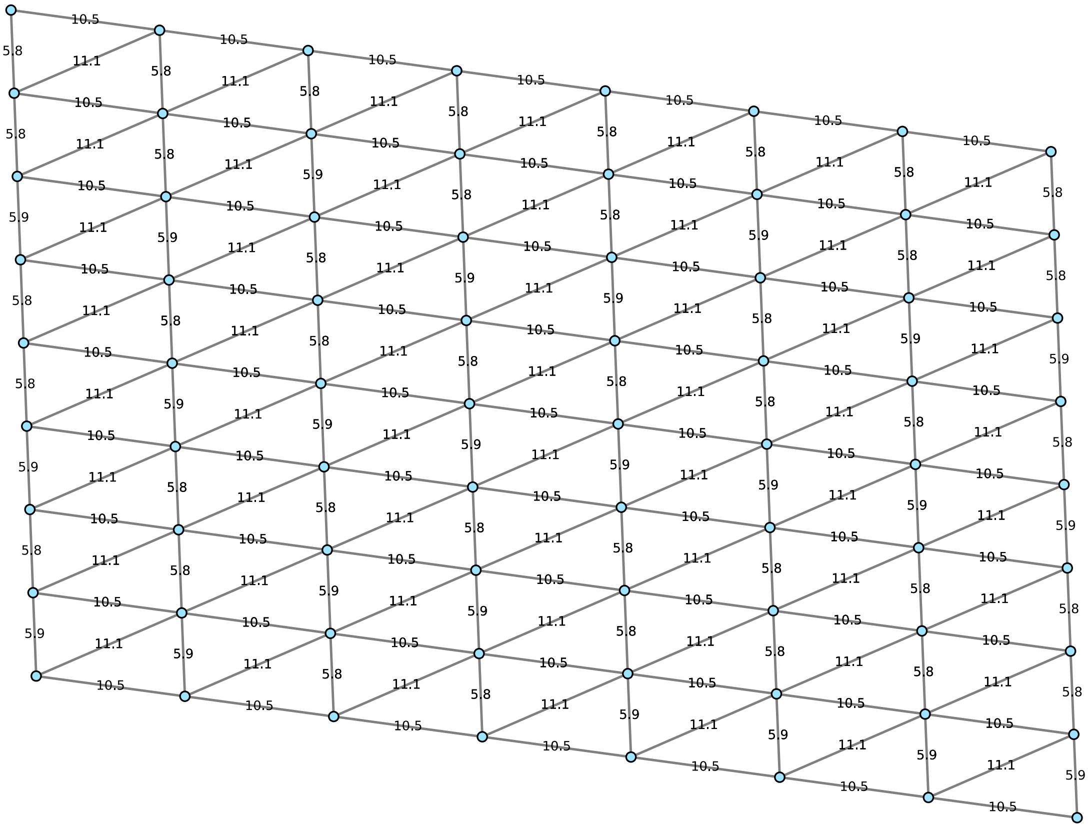
DK, Baltic Sea, Middelgrunden, 2001
20 x Bonus B76/2000
sources: ENS, 4C Offshore
$H = 64.0$ m, $D = 76.0$ m, $P_{rated,T} = 2.0$ MW, $p_{A_{rotor}} = 440.9$ W/m^2
$A_{WF} = 0.0$ km^2, $P_{WF} = 40.0$ MW,

DK, HORNS REV 1



DK, North Sea, Horns Rev 1, 2002
80 x Vestas V80-2.0 MW
sources: ENS, 4C Offshore
$H = 70.0$ m, $D = 80.0$ m, $P_{rated,T} = 2.0$ MW, $p_{A_{rotor}} = 397.9$ W/m^2
$A_{WF} = 19.6$ km^2, $P_{WF} = 160.0$ MW, $p_{A_{WF}} =$ 8.2 MW/km^2, $p_{A_{WF}}* =$ 6.4 MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 8.7$, $d_{\perp} = 6.1$, $d* = 7.0$

DK, NYSTED

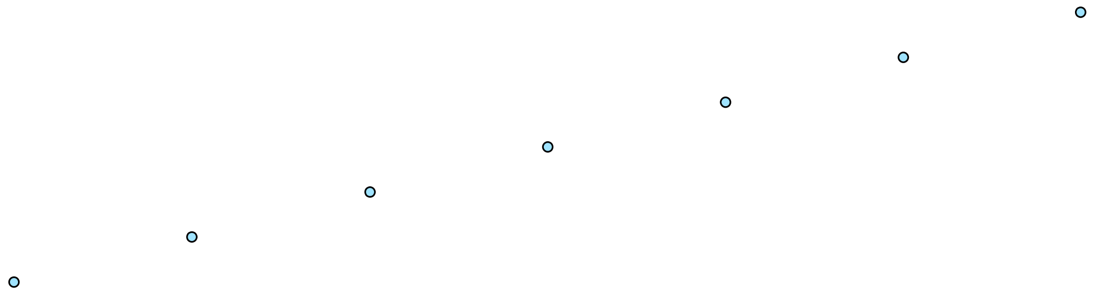


DK, Baltic Sea, Nysted, 2003
72 x Siemens SWT-2.3-83
sources: ENS, 4C Offshore
$H = 69.0$ m, $D = 82.4$ m, $P_{rated,T} = 2.3$ MW, $p_{A_{rotor}} = 431.3$ W/m^2
$A_{WF} = 23.0$ km^2, $P_{WF} = 165.6$ MW, $p_{A_{WF}} = 7.2$ MW/km^2, $p_{A_{WF}}* = 5.6$ MW/km^2
$\phi = 225.0°$, $d_\parallel = 7.8$, $d_\perp = 5.0$, $d* = 7.8$

DK, SAMSØ

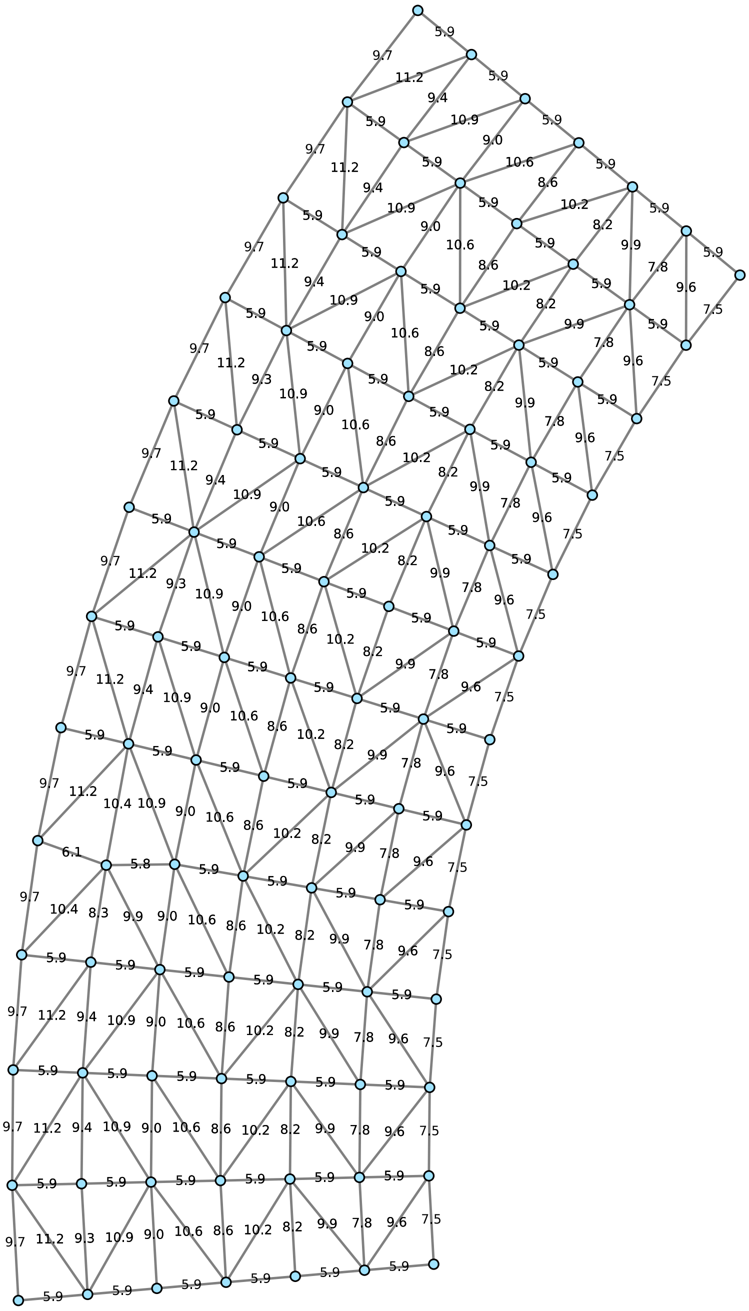
DK, Baltic Sea, Samsø, 2003
10 x Siemens SWT-2.3-82
sources: ENS, 4C Offshore
$D = 82.4$ m, $P_{rated,T} = 2.3$ MW, $p_{A_{rotor}} = 431.3$ W/m^2
$A_{WF} = 0.0$ km^2, $P_{WF} = 23.0$ MW,

DK, SPROGØ



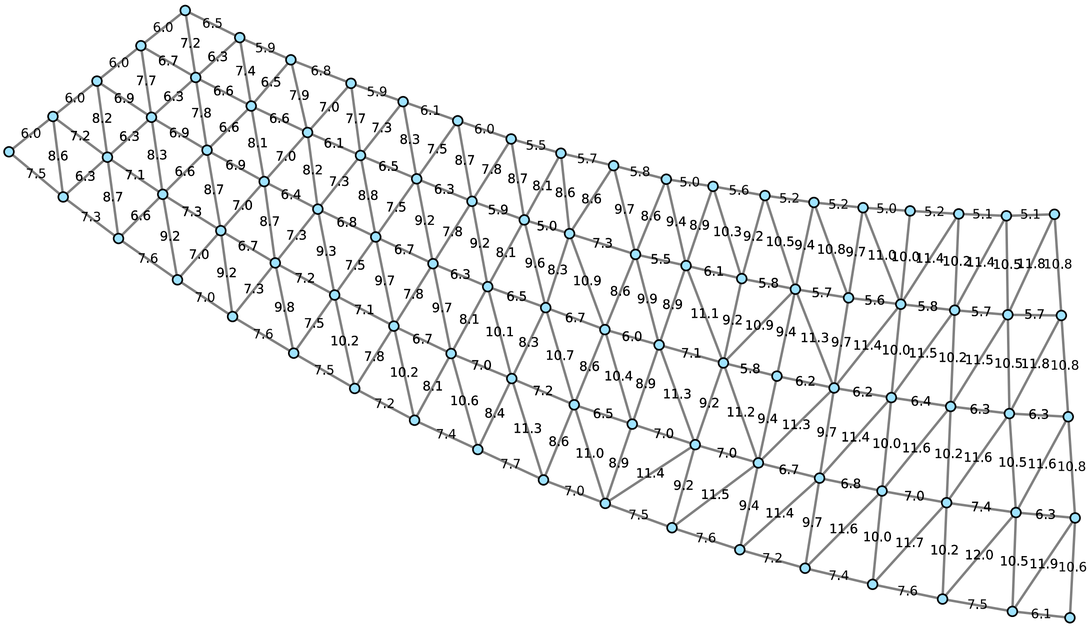
DK, Baltic Sea, Sprogø, 2009
07 x Vestas V90-3.0 MW
sources: ENS, 4C Offshore
$H = 70.0$ m, $D = 90.0$ m, $P_{rated,T} = 3.0$ MW, $p_{A_{rotor}} = 471.6$ W/m^2
$A_{WF} = 0.0$ km^2, $P_{WF} = 21.0$ MW,

DK, HORNS REV 2



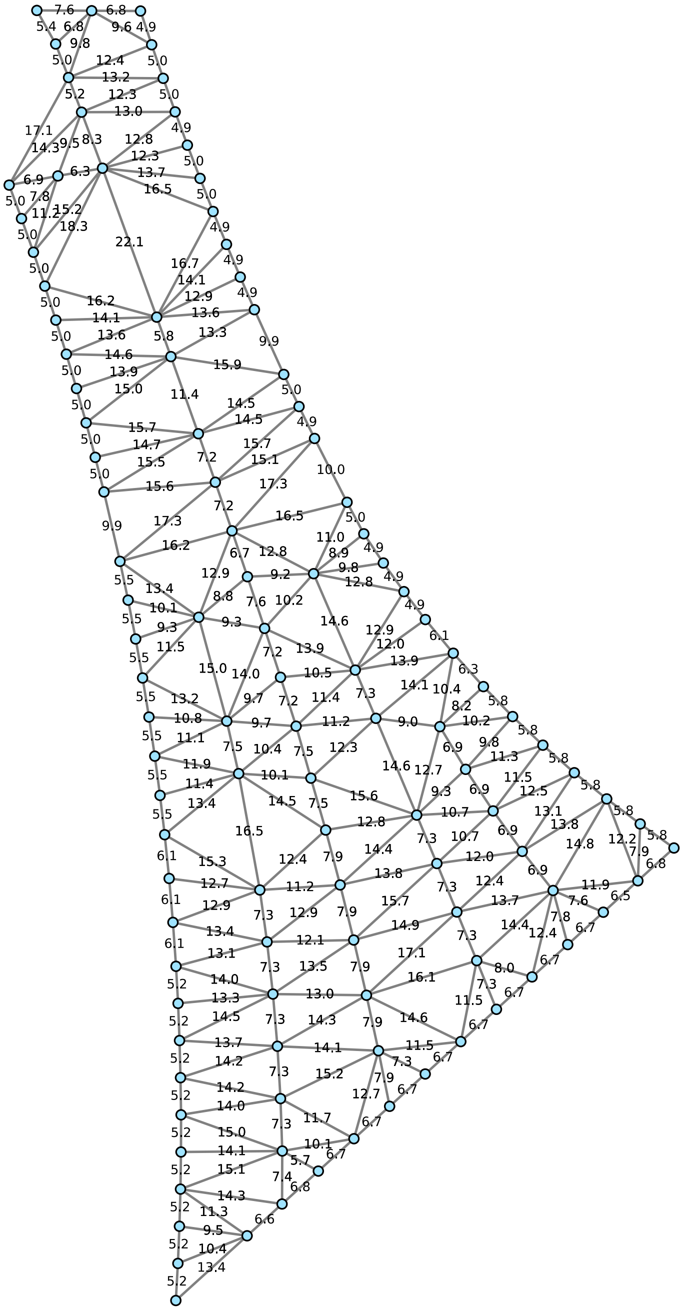
DK, North Sea, Horns Rev 2, 2010
91 x Siemens SWT-2.3-93
sources: ENS, 4C Offshore
$H = 68.0$ m, $D = 93.0$ m, $P_{rated,T} = 2.3$ MW, $p_{A_{rotor}} = 338.6$ W/m^2
$A_{WF} = 31.4$ km^2, $P_{WF} = 209.3$ MW, $p_{A_{WF}} = 6.7$ MW/km^2, $p_{A_{WF}}* = 5.3$ MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 9.3$, $d_{\perp} = 5.4$, $d* = 7.1$

DK, RØDSAND 2



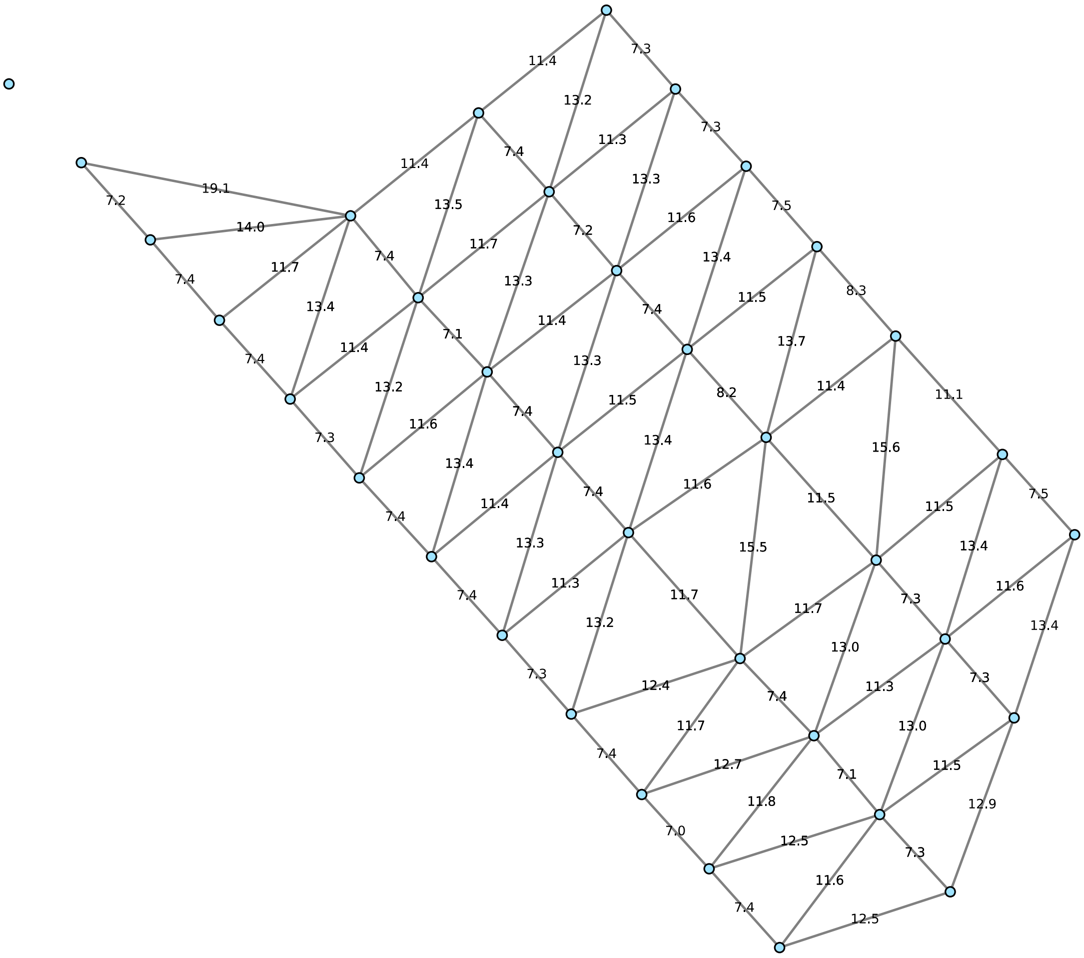
DK, Baltic Sea, Rødsand 2, 2010
90 x Siemens SWT-2.3-93
sources: ENS, 4C Offshore
$H = 68.5$ m, $D = 93.0$ m, $P_{rated,T} = 2.3$ MW, $p_{A_{rotor}} = 338.6$ W/m^2
$A_{WF} = 31.7$ km^2, $P_{WF} = 207.0$ MW, $p_{A_{WF}} =$ 6.5 MW/km^2, $p_{A_{WF}}* =$ 4.9 MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 9.4$, $d_{\perp} = 5.8$, $d* = 7.3$

DK, ANHOLT



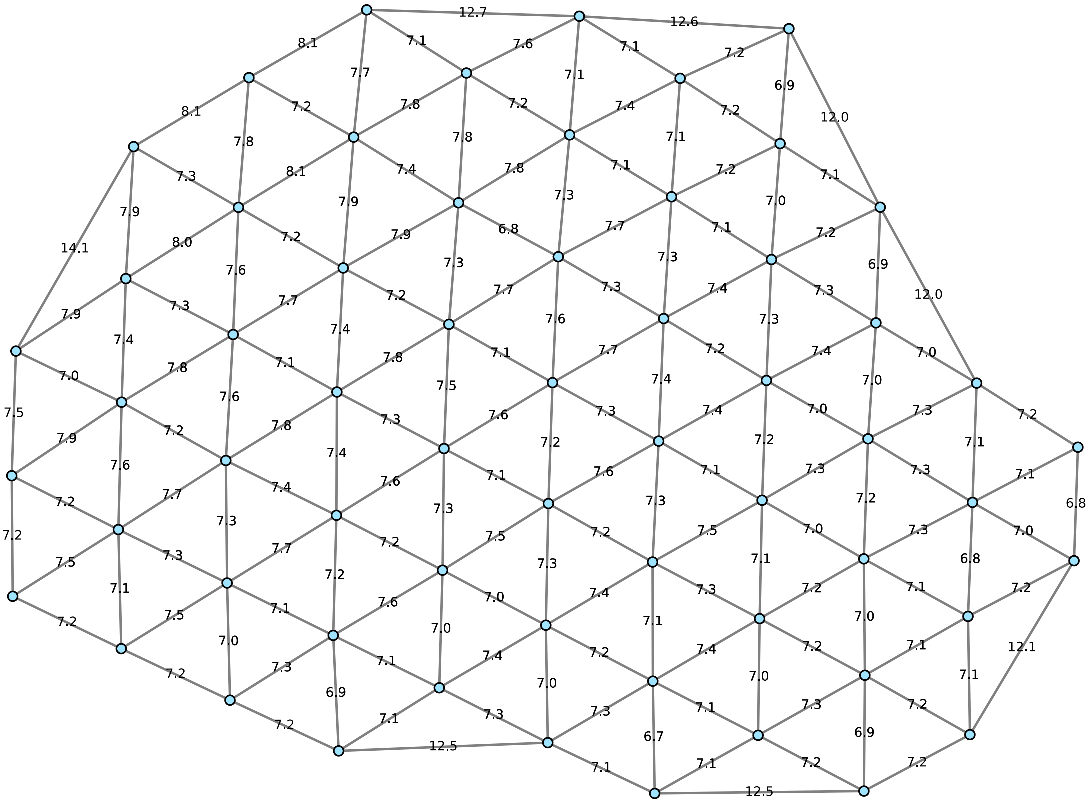
DK, Baltic Sea, Anholt, 2013
111 x Siemens SWT-3.6-120
sources: ENS, 4C Offshore
$H = 81.6$ m, $D = 120.0$ m, $P_{rated,T} = 3.6$ MW, $p_{A_{rotor}} = 318.3$ W/m^2
$A_{WF} = 89.4$ km^2, $P_{WF} = 399.6$ MW, $p_{A_{WF}} = 4.5$ MW/km^2, $p_{A_{WF}}* = 3.0$ MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 9.9$, $d_{\perp} = 6.0$, $d* = 9.2$

NL, EGMOND AAN ZEE



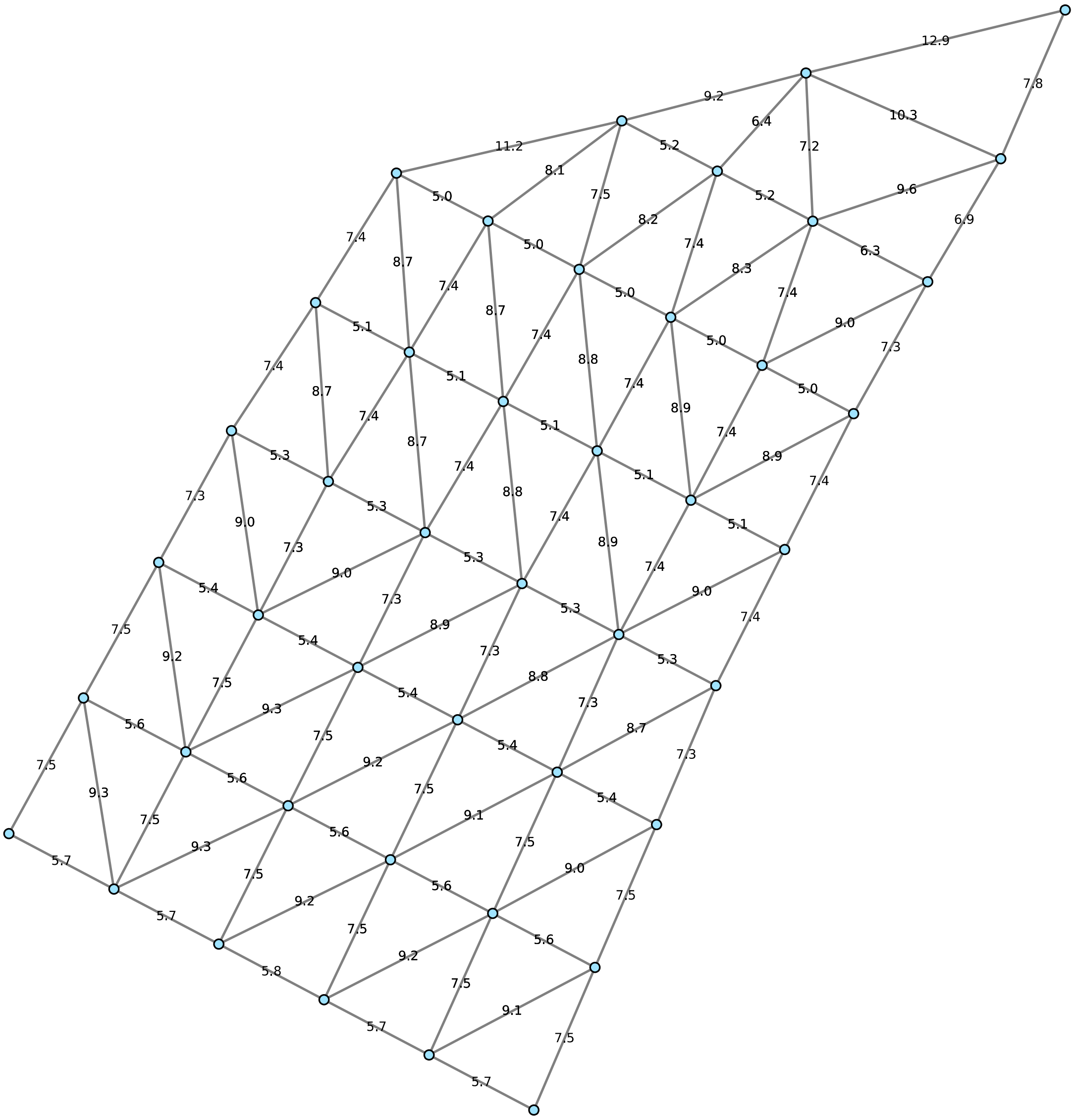
NL, North Sea, Egmond aan Zee, 2007
36 x Vestas V90-3.0 MW
sources: WindStats.nl, 4C Offshore
$H = 70.0$ m, $D = 90.0$ m, $P_{rated,T} = 3.0$ MW, $p_{A_{rotor}} = 471.6$ W/m^2
$A_{WF} = 16.7$ km^2, $P_{WF} = 108.0$ MW, $p_{A_{WF}} =$ 6.5 MW/km^2, $p_{A_{WF}}* =$ 4.2 MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 11.9$, $d_{\perp} = 7.3$, $d* = 9.4$

NL, PRINSES AMALIA



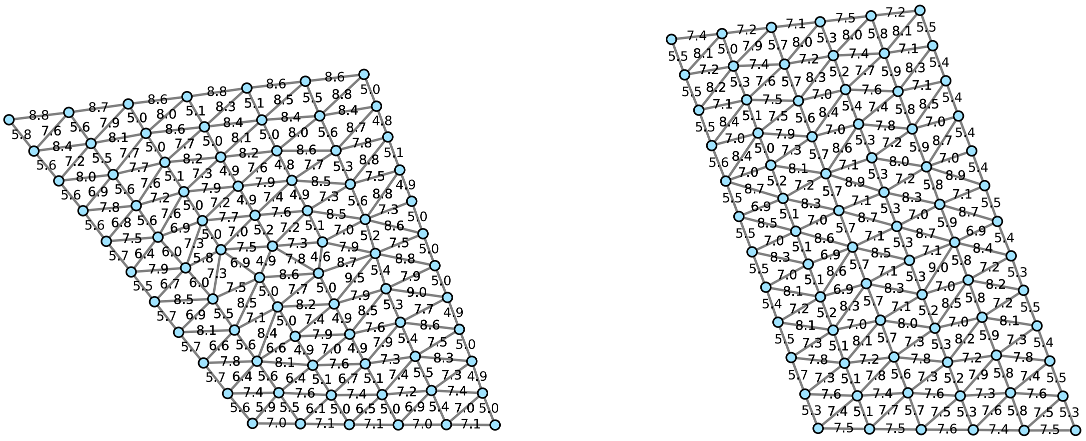
NL, North Sea, Prinses Amalia, 2008
80 x Vestas V80-2.0MW
sources: WindStats.nl, 4C Offshore
$D = 80.0$ m, $P_{rated,T} = 2.0$ MW, $p_{A_{rotor}} = 397.9$ W/m^2
$A_{WF} = 14.6$ km^2, $P_{WF} = 160.0$ MW, $p_{A_{WF}} =$ 10.9 MW/km^2, $p_{A_{WF}}* =$ 9.5 MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 7.4$, $d_{\perp} = 6.9$, $d* = 5.7$

NL, LUCHTERDUINEN



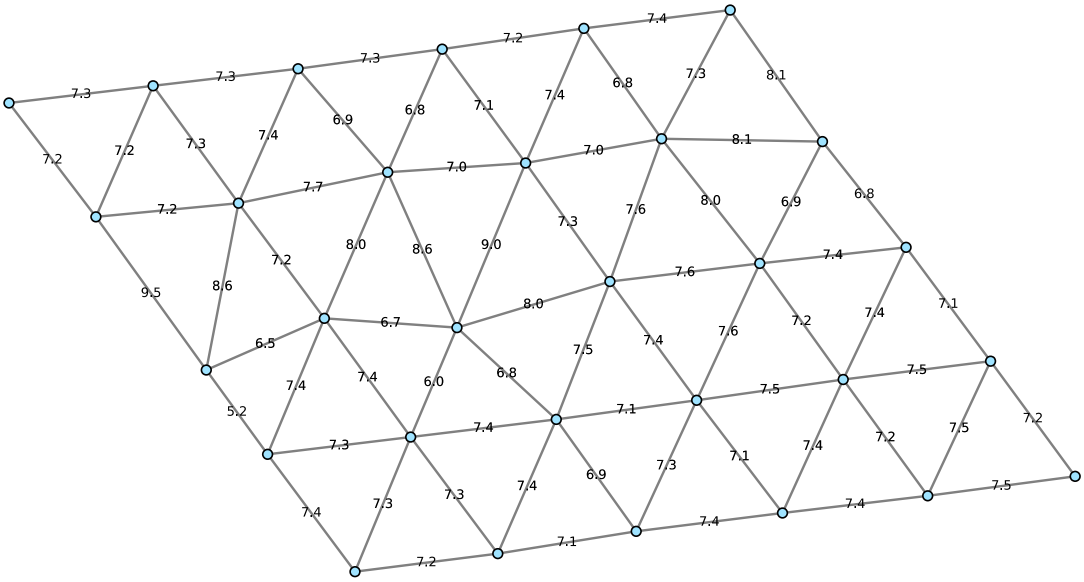
NL, North Sea, Luchterduinen, 2015
43 x MHI Vestas V112-3.0 MW
sources: WindStats.nl, 4C Offshore
$H = 81.0$ m, $D = 112.0$ m, $P_{rated,T} = 3.0$ MW, $p_{A_{rotor}} = 304.5$ W/m^2
$A_{WF} = 15.9$ km^2, $P_{WF} = 129.0$ MW, $p_{A_{WF}} =$ 8.1 MW/km^2, $p_{A_{WF}}* =$ 5.9 MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 7.7$, $d_{\perp} = 5.2$, $d* = 6.3$

NL, GEMINI



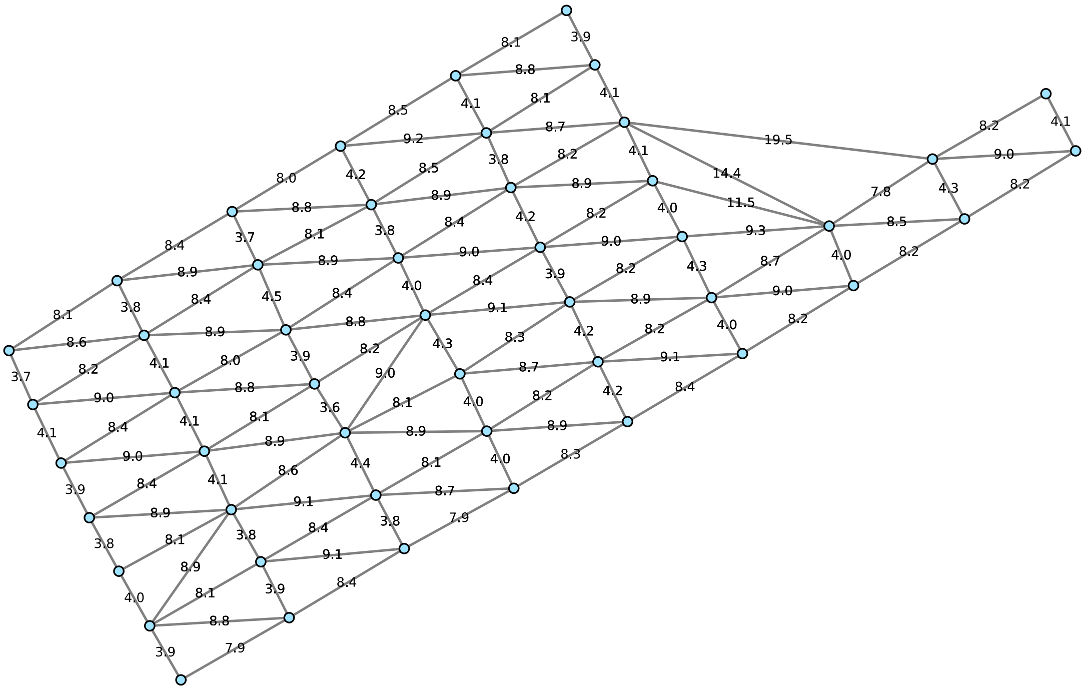
NL, North Sea, Gemini, 2017
150 x Siemens SWT-4.0-130
sources: WindStats.nl, 4C Offshore
$H = 89.0$ m, $D = 130.0$ m, $P_{rated,T} = 4.0$ MW, $p_{A_{rotor}} = 301.4$ W/m^2
$A_{WF} = 73.7$ km^2, $P_{WF} = 600.0$ MW, $p_{A_{WF}} = 8.1$ MW/km^2, $p_{A_{WF}}* = 6.3$ MW/km^2
$\phi = 225.0°$, $d_\parallel = 7.4$, $d_\perp = 5.1$, $d* = 6.1$

UK, KENTISH FLATS



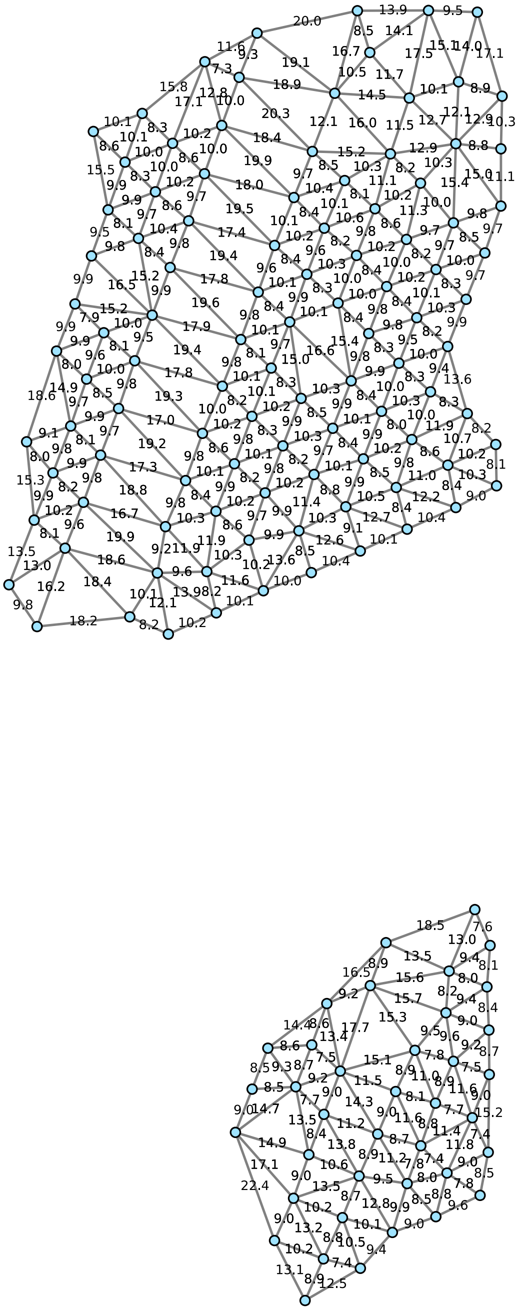
UK, North Sea, Kentish Flats, 2005
30 x Vestas V90-3.0 MW
sources: OSM, 4C Offshore
$H = 70.0$ m, $D = 90.0$ m, $P_{rated,T} = 3.0$ MW, $p_{A_{rotor}} = 471.6$ W/m^2
$A_{WF} = 7.5$ km^2, $P_{WF} = 90.0$ MW, $p_{A_{WF}} =$ 11.9 MW/km^2, $p_{A_{WF}}* =$ 8.0 MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 7.4$, $d_{\perp} = 6.7$, $d* = 6.8$

UK, GUNFLEET SANDS



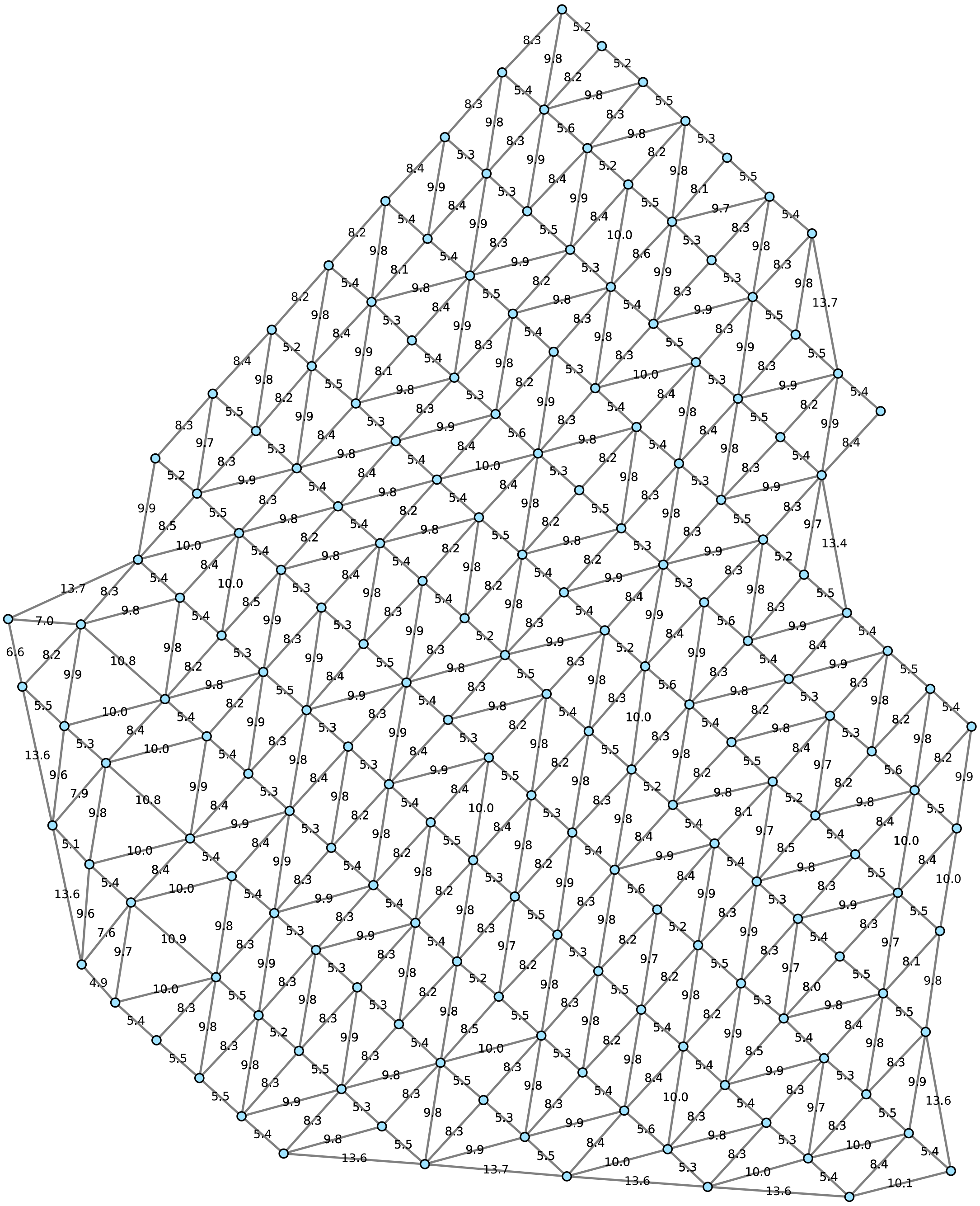
UK, North Sea, Gunfleet Sands, 2010
48 x Siemens SWT-3.6-107
sources: OSM, 4C Offshore
$H = 75.0$ m, $D = 107.0$ m, $P_{rated,T} = 3.6$ MW, $p_{A_{rotor}} = 400.4$ W/m^2
$A_{WF} = 13.6$ km^2, $P_{WF} = 172.8$ MW, $p_{A_{WF}} =$ 12.7 MW/km^2, $p_{A_{WF}}* =$ 9.3 MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 9.3$, $d_{\perp} = 3.8$, $d* = 5.8$

UK, GREATER GABBARD



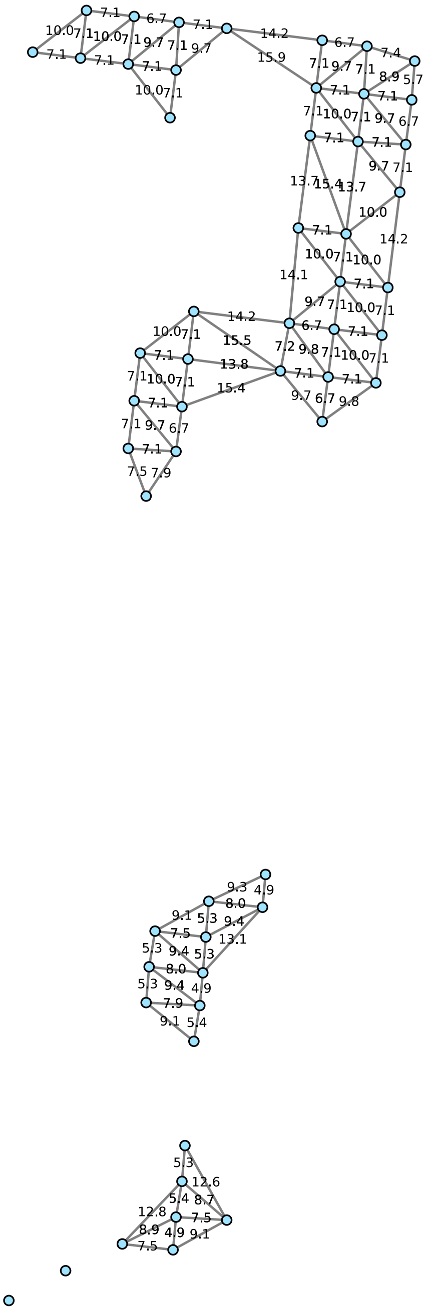
UK, North Sea, Greater Gabbard, 2013
140 x Siemens SWT-3.6-107
sources: OSM, 4C Offshore
$H = 77.5$ m, $D = 107.0$ m, $P_{rated,T} = 3.6$ MW, $p_{A_{rotor}} = 400.4$ W/m^2
$A_{WF} = 125.7$ km^2, $P_{WF} = 504.0$ MW, $p_{A_{WF}} = 4.0$ MW/km^2, $p_{A_{WF}}* = 3.3$ MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 10.3$, $d_{\perp} = 8.0$, $d* = 9.8$

UK, LONDON ARRAY



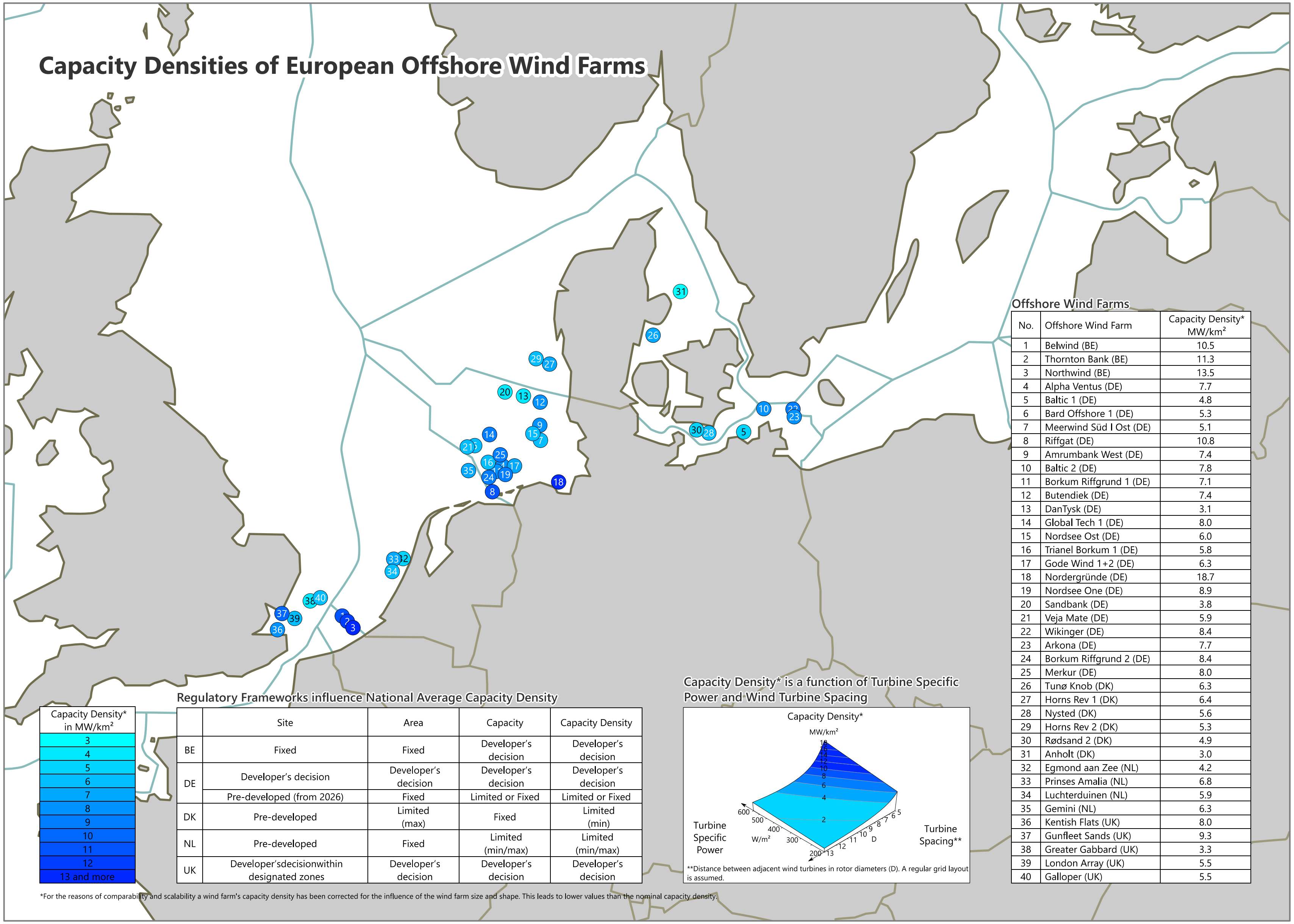
UK, North Sea, London Array, 2013
175 x Siemens SWT-3.6-120
sources: OSM, 4C Offshore
$H = 87.0$ m, $D = 120.0$ m, $P_{rated,T} = 3.6$ MW, $p_{A_{rotor}} = 318.3$ W/m^2
$A_{WF} = 101.3$ km^2, $P_{WF} = 630.0$ MW, $p_{A_{WF}} = 6.2$ MW/km^2, $p_{A_{WF}}* = 5.5$ MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 8.3$, $d_{\perp} = 5.3$, $d* = 6.7$

UK, GALLOPER



UK, North Sea, Galloper, 2018
56 x Siemens SWT-6.3-154
sources: OSM, 4C Offshore
$D = 154.0$ m, $P_{rated,T} = 6.3$ MW, $p_{A_{rotor}} = 338.2$ W/m^2
$A_{WF} = 36.4$ km^2, $P_{WF} = 352.8$ MW, $p_{A_{WF}} = $ 9.7 MW/km^2, $p_{A_{WF}}* = $ 5.5 MW/km^2
$\phi = 225.0°$, $d_{\parallel} = 8.6$, $d_{\perp} = 5.9$, $d* = 6.9$

INFOGRAPHIC



Capacity Densities of European Offshore Wind Farms

Capacity Density* in MW/km²
3
4
5
6
7
8
9
10
11
12
13 and more

Regulatory Frameworks influence National Average Capacity Density

	Site	Area	Capacity	Capacity Density
BE	Fixed	Fixed	Developer's decision	Developer's decision
DE	Developer's decision	Developer's decision	Developer's decision	Developer's decision
	Pre-developed (from 2026)	Fixed	Limited or Fixed	Limited or Fixed
DK	Pre-developed	Limited (max)	Fixed	Limited (min)
NL	Pre-developed	Fixed	Limited (min/max)	Limited (min/max)
UK	Developer'sdecisionwithin designated zones	Developer's decision	Developer's decision	Developer's decision

Capacity Density* is a function of Turbine Specific Power and Wind Turbine Spacing

**Distance between adjacent wind turbines in rotor diameters (D). A regular grid layout is assumed.

Offshore Wind Farms

No.	Offshore Wind Farm	Capacity Density* MW/km²
1	Belwind (BE)	10.5
2	Thornton Bank (BE)	11.3
3	Northwind (BE)	13.5
4	Alpha Ventus (DE)	7.7
5	Baltic 1 (DE)	4.8
6	Bard Offshore 1 (DE)	5.3
7	Meerwind Süd I Ost (DE)	5.1
8	Riffgat (DE)	10.8
9	Amrumbank West (DE)	7.4
10	Baltic 2 (DE)	7.8
11	Borkum Riffgrund 1 (DE)	7.1
12	Butendiek (DE)	7.4
13	DanTysk (DE)	3.1
14	Global Tech 1 (DE)	8.0
15	Nordsee Ost (DE)	6.0
16	Trianel Borkum 1 (DE)	5.8
17	Gode Wind 1+2 (DE)	6.3
18	Nordergründe (DE)	18.7
19	Nordsee One (DE)	8.9
20	Sandbank (DE)	3.8
21	Veja Mate (DE)	5.9
22	Wikinger (DE)	8.4
23	Arkona (DE)	7.7
24	Borkum Riffgrund 2 (DE)	8.4
25	Merkur (DE)	8.0
26	Tunø Knob (DK)	6.3
27	Horns Rev 1 (DK)	6.4
28	Nysted (DK)	5.6
29	Horns Rev 2 (DK)	5.3
30	Rødsand 2 (DK)	4.9
31	Anholt (DK)	3.0
32	Egmond aan Zee (NL)	4.2
33	Prinses Amalia (NL)	6.8
34	Luchterduinen (NL)	5.9
35	Gemini (NL)	6.3
36	Kentish Flats (UK)	8.0
37	Gunfleet Sands (UK)	9.3
38	Greater Gabbard (UK)	3.3
39	London Array (UK)	5.5
40	Galloper (UK)	5.5

*For the reasons of comparability and scalability a wind farm's capacity density has been corrected for the influence of the wind farm size and shape. This leads to lower values than the nominal capacity density.

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