Capacity density considerations in meeting Poland's ambitious offshore wind targets

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Poland has set itself an ambitious offshore wind target to have 10.9 GW of installed capacity, either operational or under development, by 2027. This is enshrined in the recent Poland Offshore Wind Energy Act[1], that came into force in February 2021. As bold as this is, it raises many questions; especially given there aren't any offshore wind farms currently operational in Polish waters.

So, is there enough space? At first glance, the Polish Exclusive Economic Zone (EEZ), which covers an area of more than 22,500 km^2 (approximately 6% of the total area of the south Baltic Sea) provides a good amount of sea floor for Poland to achieve its energy targets. However, when considering the competition offshore wind faces, with everything from fisheries to wildlife conservation, not to mention other energy sectors, is this a problem?

The Polish Government has already addressed this need for balance with the introduction of the Maritime Spatial Development Plan, in April 2021. The Plan coordinates spatial use of Polish waters, balancing economic and environmental needs and uses. The combined result of this Plan and the Offshore Energy Act, is the designation of three offshore wind farm development areas, with fixed boundaries, which are consented and tendered by the Government. At present, offshore wind energy can only be developed in these areas.

Interestingly, although there are no defined fixed limits for capacity density[2] generally set by the Polish authorities, one of the qualifying criteria in the ongoing seabed lease, do set a minimum for this metric. That's to say 8 MW/km^2 for any wind farm, and this doesn't include exclusions such as environmentally protected areas, wrecks, or existing infrastructure. A cursory glance would suggest this seems like an excessively high minimum, given the amount of seabed being offered up. Could this be from a desire to maximise the chances of meeting the ambitious 10.9 GW target?

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[1] Act of 18 December 2020 on the Promotion of Electricity Generation in Offshore Wind Farms; available at https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20210000234/O/D20210234.pdf

[2] The ratio of the wind farm's rated capacity to the wind farm's site area in [MW/km^2]

So, to answer our first question 'is there enough space?' – in short yes. The installed capacity required to meet the target of the act can comfortably fit in the three identified areas. The more complex question then is, what are the challenges caused by this capacity density threshold of the *8 MW/km²* set by the regulatory authorities? This paper explores the overall technical feasibility of this target and opens a discussion on the potential challenges.

To start this exploratory work, WT has reviewed the rules of the application process for Polish seabed leases and set them against five other major European offshore wind markets, looking at observed capacity densities for a comprehensive set of operational projects in these countries. The data for this work has been extracted from the platform 4COffshore[3].

Table 1 – Selected countries regulatory schemes based on the Baltic LINes publication[4] and WT experience

	Development areas	Site Boundaries	Wind Farm Total Rated Power	Capacity Density
BE	Fixed	Fixed	Developer's decision	Developer's decision
DE	Developer's decision	Developer's decision	Developer's decision	Developer's decision
DK	Limited (max)	Pre-developed	Fixed	Limited (min)
NL	Fixed	Pre-developed	Limited (max)	Limited (min/max)
UK	Developer's decision	Developer's decision	Developer's decision	Developer's decision
PL	Fixed	Fixed	Developer's decision	Limited (min)

The review reveals those regulatory mechanisms in relation to exclusivity; wind farm rated capacity; and capacity density requirements, vary considerably among the markets analysed. This gives us an interesting spread in observed capacity density and size of wind farms, as shown below.

[3] https://www.4coffshore.com/; accessed February 2022.

[4] Baltic LINes, "Capacity Densities of European Offshore Wind Farms", Report conducted by Deutsche WindGuard GmbH, Hamburg, June 2018

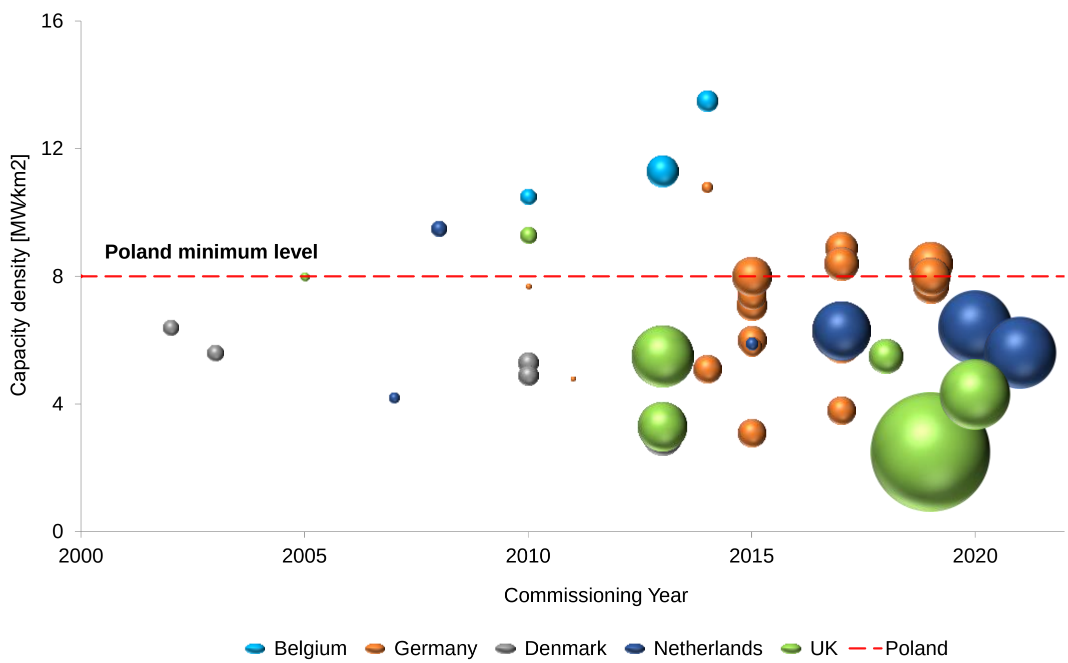

Figure 1 – Offshore wind farm capacity density by country, size and maturity. A sample of projects representative of each market has been used for the plot. Each sphere refers to a project, and the size of the spheres depicts the size of the project as installed capacity (MW).

Another way of looking at this data is by plotting the quantified mean and range of wind farm capacity density for each of the markets.

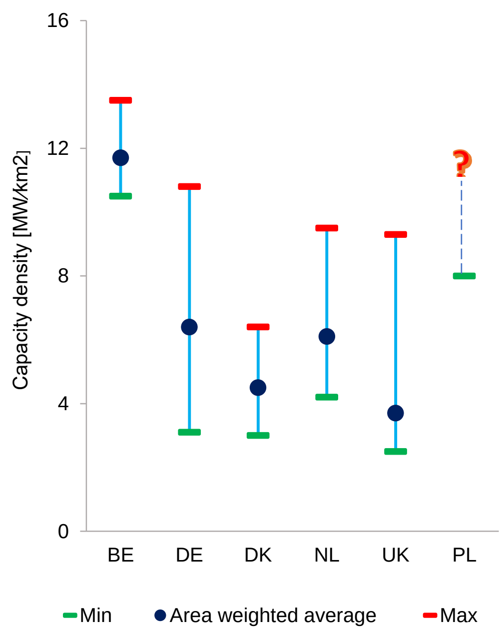

Figure 2 – Mean and range of wind farm capacity density per market

However, variations and differing needs across sites and countries means developing generalised conclusions about capacity density is a challenge.

From an engineering perspective, maximizing array efficiency and therefore energy production is what will drive the design principals around capacity density decisions. In other words lower capacity density generally delivers lower turbine interaction losses and so maximises energy production.

However, it's not actually that simple. Country siting regulations, as shown in Table 1, vary widely which, combined with the development area available, strongly affect the mean wind farm capacity density of each country. Belgium is a perfect example of this. Space is scarce for offshore wind, so developers need to make the most of the area available, resulting in a higher capacity density. For countries with more seabed available, we see more freedom to use larger areas. And, in countries where the decision on wind farm installed capacity stays with the developer, lower mean capacity densities are the norm. The UK is a particularly strong example of this, due to its larger EEZ.

So, what about Poland? By establishing a minimum capacity density for the ongoing lease auction, the Polish government seems to be signalling that its primary focus is on maximizing the seabed, to achieve the targeted installed capacity for the country. That decision means Poland may be following the Belgium model, despite the larger EEZ available in this market.

There's more to it than that though. As well as Polish projects having one of the highest turbine capacity densities, these projects are mainly at the upper end in terms of size (area), compared to other operational western European projects. For example, in the UK, projects a of a similar installed capacity are being constructed, albeit with a much lower capacity density. Furthermore, wind farms in Poland are being planned in clusters where neighbouring wind farms will significantly impact each other. So, what does this all mean? In short, this is something the industry hasn't really seen before and so may require several technical innovations to meet the challenges.

Although using site areas as intensively as possible, to meet minimum capacity density requirements, may increase the overall energy production, there are downsides: Increased turbine interaction energy losses (internal and external wakes and global blockage effects); as well as increased wake-induced fatigue loads for downstream turbines, which may lead to reduced lifetimes and/or premature damage of the asset. In other words, any marginal gains may be lost, and you might actually see an increased Levelised Cost of Energy (LCoE).

This issue could be further compounded by the ever-increasing turbine rotor blade size. Given the timescale of projects, it is very likely that the first offshore wind farms in Poland will use larger turbines than those already installed at existing projects, or planned for projects in more advanced stages of development. These larger turbines are trending towards a lower specific power[5], meaning, though they have longer blades and greater swept areas, the nameplate capacity is not increasing proportionately.

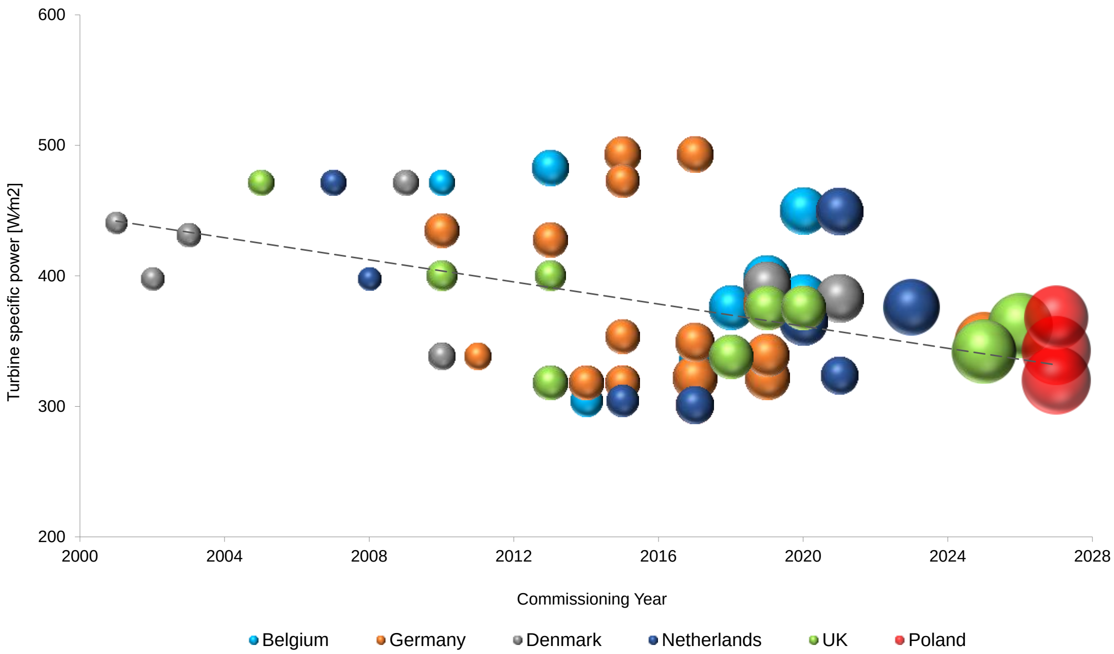

Figure 3 – Trend of turbine specific power observed in Europe from 2000. Each sphere refers to a turbine model, and the size of the spheres depicts the rotor diameter.

The trend of decreasing turbine specific power in the UK offshore wind market has previously been assessed[6] and has been shown to result in better low-wind performance and better capacity factors for offshore wind farms (ie. the ratio of net energy yield production to the maximum possible energy yield production). Whilst this explains the latest trend in decreasing turbine specific power, it has interesting implications for layout design and resulting capacity densities.

As a result of this thinking, WT has investigated this further by analysing potential scenarios that consider how the following factors might impact offshore wind farm layout design in Poland:

- The trend in future turbine technology;

[5] The ratio of turbine nameplate rated power to turbine rotor swept area [W/m^2]

[6] Potential to improve load factor of offshore wind farms in the UK to 2035 - GOV.UK (www.gov.uk)

- How this translates to project capacity density for Poland's regulatory approach;
- What this means for the resulting impact on turbine interaction effects.

Three scenarios have been modelled based on a theoretical project with the following parameters:

- Site area of ~110 km^2, seen to be representative of typical offshore project development areas in Poland;
- 1200 MW installed capacity, in order to achieve the minimum 8 MW/km^2 capacity density[7] set by Polish regulators;
- Regular turbine spacing of approximately 7 rotor diameters (D) in the prevailing wind direction (assumed to be westerly) and 4 D in the transverse directions in a rectangular grid;
- Approximately 10.0 m/s mean wind speed at the proposed turbine hub heights.

The three scenarios have considered future turbine technology assumptions as shown in the table below:

Table 2 – **Future turbine technology assumptions and resulting project scenario assumptions**

	Scenario 1	Scenario 2	Scenario 3
Turbine nameplate rated power [MW]	15	20	25
Hub height [m above Mean Sea Level]	140	160	180
Rotor diameter [m]	236	270	300
Wind Farm capacity [MW]	1200	1200	1200
Number of turbines	80	60	48

The turbine rotor diameters have been determined to obtain a turbine specific power of between 340 W/m^2 and 360 W/m^2, a range defined based on the trend observed in Figure 3.

Using the above assumptions, the theoretical turbine layouts shown below have been put forward as working scenarios.

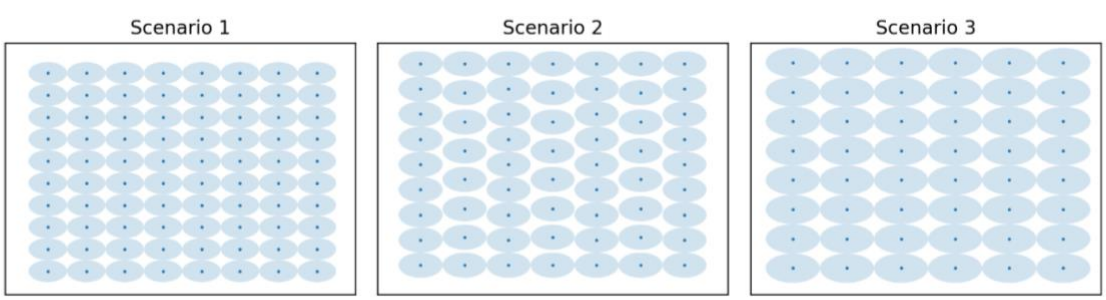

Figure 4 – Layout scenarios considered. Ellipses illustrate the 7D by 4D turbine spacing assumed.

[7] The wind farm area used to derive the capacity density has been calculated using Delaunay Triangulation, as proposed by the Danish Energy Agency; https://ens.dk/sites/ens.dk/files/Vindenergi/area_calculation.pdf.

WT has calculated the turbine interaction effects for the scenarios considered using the Eddy Viscosity wake model, within WindFarmer Analyst, with Large Wind Farm correction, including an assessment of the blockage effects. The results are shown in the graph below:

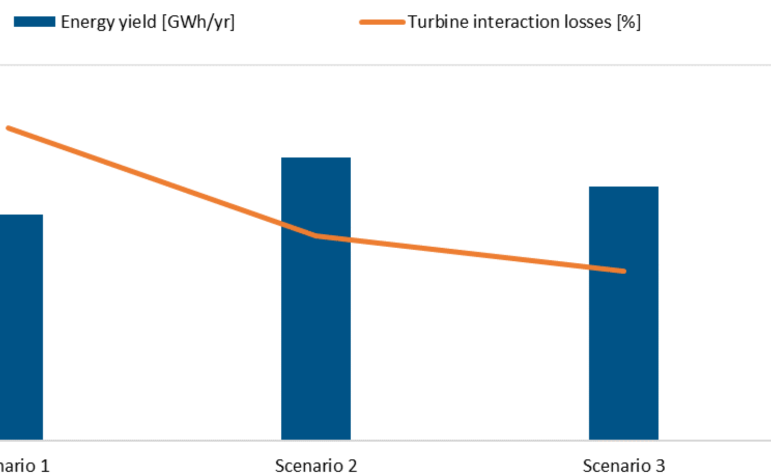

Figure 5 – Indicative energy yield production (after turbine interaction effects) and turbine interaction effect losses estimated for the three scenarios considered.

This study indicates that, in this situation (fixed site area, fixed project installed capacity, and minimum capacity density of 8 MW/km^2), increasing the turbine size from 15 MW to 25 MW could achieve lower turbine interaction losses, despite the larger rotor diameters.

However, it appears there is a sweet spot in terms of turbine size (MW and rotor diameter) for the Polish offshore wind market. A balance must be reached between the additional energy yield that comes from using larger turbines, and the reduction in yield that comes from having fewer turbines (with larger swept areas but with proportionally lower nominal capacities). In this example, the drop in number of turbines from 60 x 20 MW turbines in Scenario 2 to 48 x 25 MW turbines in Scenario 3, is not compensated by the additional yield that can be generated by the 25 MW turbine.

It should be noted that this study does not take into account any other technical loss factors such as availability and electrical efficiency, which will also be impacted by the project configuration. Nor does it consider alternative turbine layout design techniques such as edge-packing or irregular grids, which will have some impact on the resulting turbine interaction effects (both internal wakes and blockage effects). Notwithstanding this, depending on the specific market, this study still serves to illustrate that perhaps ever-larger turbine models may not always be the obvious choice in achieving ever-lower cost of energy for offshore wind farms.

Given what has been discussed, it seems likely that Poland will not see the large spread of project capacity densities seen elsewhere. When designing layouts, developers will try to maximize energy yield and asset life by spacing the turbines out as much as possible - whilst still sticking to the minimum turbine density set. As is, simply by complying with the minimum capacity density requirements of 8 MW/km^2, developers will already see increased turbine interaction effects in their projects, and all the issues that come with it (increased energy losses and increased turbine loading primarily). Therefore, logically, they will seek to avoid capacity densities above the minimum prerequisite.

Interestingly, another possible outcome of the regulatory conditions in Poland may be that developers buck the trend of adopting turbine models with increasing rated power, and use turbine models that deliver higher energy yield output, whilst accepting the higher turbine interaction effects that will bring.

Implementation of wake management techniques (for example wake steering or axial induction control) could be a solution to mitigate those higher wake effects, reduce structural loads, extend project lifetime and, consequently decrease LCoE.

Careful layout design and optimization will also have a key role to play in the successful optimization of offshore wind farm projects in Poland, whilst meeting regulatory requirements. Though this can help minimize turbine interaction effects, there are multiple factors which impact the overall optimal design of a layout. These include, bathymetry, soil and metocean conditions (impacting feasibility of certain foundation types, foundation design and cost), as well as electrical system design (impacting electrical efficiency and balance of plant cost). A holistic approach to all these aspects will be crucial to delivering an optimized project.

Finally, as turbine technology continues to evolve, the industry may see more tailored turbines and solutions offered by manufacturers to adapt to specific market requirements. Developers should try to take advantage of the relatively low wind and wave extremes seen in this part of the Baltic Sea[8], and push the design envelope to focus on addressing high waked-turbulence conditions rather than other design drivers. This might assist developers of Polish projects to overcome the technical challenges described in this article. In the end, the relatively benign conditions of the

[8] V. Alari, Marine Systems Institute at Tallinn University of Technology, “Multi-Scale Wind Wave Modeling in the Baltic Sea”, Tallinn, September 2013.

southern Baltic Sea may come to be of great benefit to the offshore wind industry there.

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Marceli is a senior renewable energy expert with 14 years of professional experience in the wind energy sector. Prior to joining WT, he spent a decade working at DNV, where he became Head of Section for Wind Project Development and Analytics. His focus was conducting wind energy assessments and key development support work for the Central and Eastern European markets. Marceli has overseen the delivery of wind resource and energy yield analyses and related services for over 20 GW of installed capacity, including 3 GW of offshore wind projects.

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Carla is a senior manager and renewable energy expert with more than 16 years of experience in the wind industry. During those 16 years Carla has held a number of technical and managerial positions as well as overseeing countless technical projects and teams on a wide variety of consultancy work across the world. Her personal expertise lies in wind resource assessment but she has been responsible for the management of teams offering a wider range of related analytical services. Her focus at WT is on combining the offshore wind resource and metocean site conditions disciplines, to manage and develop a team of experts in these combined fields.

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Marie-Anne is a senior renewable energy expert with 15 years of experience in the wind industry. Over the course of her career, Marie-Anne has provided independent, technical advisory services to onshore and offshore wind farms at various stages of development across a range of markets including the Irish, North and Baltic Seas offshore, and onshore projects in the UK, Ireland, South Africa and the Nordic region. Marie-Anne has been involved in the delivery of wind resource and energy yield related analyses for several tens of GW of offshore wind farms. She has worked on projects in Northern Europe, many of which are now operational, and has supported offshore projects in the US and Asia. She has also managed industry leading projects with the Crown Estate and Carbon Trust, improving industry understanding of offshore wind resource and reducing LCoE of offshore wind projects.