A Whole-Energy System Perspective to Floating Wind Turbines and Airborne Wind Energy in the North Sea Region

MSc Thesis

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Cover photo: Makani M600 mounted on a spar buoy (foreground) and conventional wind turbine mounted on a monopile (background) in autumn 2019. Image credits: Makani Power.

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by

Hidde Vos

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Abstract

In light of the energy transition to a fossil-free energy system, Europe is experiencing a colossal shift toward renewable energy generation. To facilitate the rapidly growing demand for clean energy, new technologies, and resources are being investigated. Airborne wind energy (AWE) and floating wind turbines have the potential to unlock untapped wind resource potential and contribute to the balancing of the system in unique ways. So far, the techno-economic potential of both technologies has only been investigated at a small scale, while the most significant benefits will likely play out on a system scale. Demonstrating the economic feasibility and additional benefits of emerging technologies in an energy system context is vital to accelerate political traction and funding.

This research aimed to find the main system-level trade-offs in integrating AWE and floating wind turbines in a highly-renewable future energy system. To do so, a modelling workflow was developed that consists of future costs and performance estimation, wind resource assessment, and integration into a high-resolution large-scale energy system cost-optimization model, based on the Calliope modelling framework. The investigated region contains 10 countries in the North Sea region. The wind resource and system balancing are hourly-resolved. Key findings include:

- Onshore AWE significantly outperforms onshore wind turbines due to higher wind resource availability.
- The main limiting factor in large-scale onshore AWE deployment is the spatial energy density.
- Offshore AWE shows highly identical performance compared to offshore wind alternatives.
- Deployment of offshore AWE is mainly cost driven.
- Floating wind turbines demonstrate great potential because of the high capacity factors that can be achieved in high wind resource areas where conventional offshore wind is not technically feasible.
- Offshore wind potential in general strongly depends on available onshore technical potential.

The outcomes show significant potential for both emerging technologies that could be realized in the near future. This study provides the first exploratory findings that lay the foundation for future studies in the context of this research topic. Multiple directions for follow-up research have been identified to quantify this potential in more detail.

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This research is part of the JustWind4All European Union Horizon Europe project which aims to support the acceleration of established and emerging wind energy technologies in Europe through just and effective governance. Grant agreement No.101083936. **Project page:** https://cordis.europa.eu/project/id/101083936.

Contents

Chapter 1

Introduction

Europe is facing a monumental shift in its energy system in the coming years in light of the transition to completely fossil-free energy generation by 2050. To facilitate this transition, vast amounts of renewable energy generation technologies are necessary.

Wind energy is regarded as one of the leading enabling technologies to facilitate the rapid growth in renewable energy demand worldwide. The most recent IPCC report even lists wind and solar energy as the most significant potential contributors to net emission reduction by 2030 (IPCC, 2022). Wind turbines are one of the most matured renewable energy technologies to date. However, the majority of global wind resource remains untapped. New technologies are being developed to open up new wind energy areas. This study assesses two major emerging wind energy technologies: Floating wind turbines and Airborne Wind Energy.

Deployment of conventional offshore wind turbines is limited by a maximal water depth of roughly 60 meters. It is estimated that around 80 percent of the total offshore wind resource in Europe lies in waters that are too deep for conventional offshore wind turbines (WindEurope, 2017). Floating wind turbines have the potential to harness this wind resource because they can operate in water depths up to 1000 meters. This opens up numerous high-wind resource regions across the globe. Furthermore, floating wind turbines usually operate further away from the coast, where the wind resource is usually higher and more constant.

Airborne wind energy (AWE) systems extract energy from wind by using flying tethered devices (Airborne Wind Europe, 2023). AWE systems operate at higher altitudes than conventional wind turbines, potentially unlocking a vast amount of wind resource that has not been exploited so far. Additionally, AWE systems require little material and have a high degree of flexibility and mobility compared to conventional wind turbines. In a recent report by the International Renewable Energy Agency, AWE was called a 'potential game changer' (IRENA, 2021).

This research aims to identify the main trade-offs that occur in implementing both floating wind turbines and AWE in a highly renewable energy system for the North Sea region. The North Sea has great wind energy potential due to the abundance of wind resource, relatively shallow waters, and proximity to leading economies in the world that are committed to transitioning to clean energy systems. Highlighting system integration benefits is paramount to gaining political traction and funding to enable faster large-scale implementation of new technologies.

To assess the potential of both AWE and FOWTs, an original modelling workflow was developed that encompasses wind resource assessment, future technology performance estimation, and integration into a high resolution, large-scale energy system optimization model based on the Calliope modelling framework (Pickering et al., 2022). The model represents a fully renewable energy-driven energy system and accounts for all energy sectors (Electricity, heat, mobility, and industry). The investigated region consists of 10 countries in the North Sea region.

This report is organized in the following order. In Chapter 2 a brief theoretical background on both technologies is provided. A literature review and identification of the research gaps is given in Chapter 3. Next, the methods for modelling the technologies are outlined in Chapter 4, Chapter 5, and Chapter 6. The results are presented in Chapter 7. Finally, Chapter 8 provides the discussion of the results, limitations, recommendations, and conclusion.

Chapter 2

Theoretical Background

This theoretical background chapter will provide an overview of floating wind turbines and AWE systems, including their principles of operation, types of platforms, development, and current state. The chapter will be divided into two sections, with the first section focusing on FOWT and the second section on AWE systems. This chapter aims to provide a comprehensive understanding of these technologies, their potential, and their limitations, which will form the basis for the subsequent analysis and discussion in the thesis report.

2.1 Floating Wind Turbines

Floating wind turbines are a type of offshore wind technology that consists of wind turbines mounted on floating platforms that are anchored to the seabed. These platforms allow turbines to be installed in deeper waters where fixed-bottom foundations are not feasible.

The development of floating wind turbines has been driven by the need to access deeper waters and increase the potential for offshore wind energy generation. Some of the most significant potential markets in the world, such as Japan and the US, have very few shallow-water offshore locations (IRENA, 2016). But also in existing offshore wind areas the added potential is significant. In Europe alone, the technical potential for floating wind is estimated at 4000 GW (IRENA, 2019). Additionally, floating wind turbines have the potential to generate more electricity than fixed-bottom turbines because they can access higher wind speeds in deeper waters.

There are three leading floating wind turbine platforms: spar buoys, tension leg platforms, and semi-submersible platforms. Spar buoys are vertical structures with a cylindrical shape that extend deep into the water, providing stability and support for the turbine by weight balancing. Tension leg platforms use a series of tensioned cables or tethers that are anchored to the seabed to hold the platform in place and provide the necessary stability. Semi-submersible platforms are partially submerged in the water using the buoyancy of the platform and sometimes additional ballast to stabilize the system.

Pilot projects have been set up in Norway, Scotland, Japan, and Portugal. The largest project to date is the Hywind Tampen project in Norway consisting of 11 wind turbines with a total capacity of 88 MW, accounting for almost half of the total installed capacity worldwide (Equinor, 2022). Multiple countries, among which Norway, Great Britain, and France, have announced that floating wind projects are included in their energy strategy for the coming years.

2.2 Airborne Wind Energy

Airborne Wind Energy (AWE) is a renewable energy technology that harnesses the kinetic energy of the wind at high altitudes using tethered wings or kites. AWE systems operate at heights between 100 and 1000 meters.

There are two main types of AWE: ground-gen and fly-gen. Ground-generation AWE is the most common type of AWE (Airborne Wind Europe, 2023), which is based on the principle of using a kite or wing tethered to a generator on the ground (Watson et al., 2019). When the wind moves the kite or wing, it pulls the tether, which drives the generator to produce electricity. The tether connects the kite to the ground-based generator. In fly-gen systems, the energy is generated onboard the flying device and transmitted to the ground station via the tether. In this report, only ground-gen systems are considered, because it is the most mature and dominant technology. Moreover, the first commercially available systems are ground-gen as well (SkySails Group, 2022a)(Kitepower, 2023).

The operation of a ground-generation system consists of two operational phases: the traction phase, where the tether is extracted and generates electrical energy at the ground station, and the recovery phase, where the kite is reeled in using a small portion of the generated electricity. The kite is equipped with a control system that allows it to fly autonomously and adjust its position in response to wind conditions. Crosswind motion is used to maximize energy production in the traction phase and minimize energy consumption in the recovery phase. Devices typically fly in a figure of eight or a helical flight path (Airborne Wind Europe, 2023).

The operation of ground-generation AWE systems is highly dependent on wind conditions, and the output power can vary depending on wind speed and direction. Therefore, advanced control systems are required to optimize the flight trajectory of the kite and maximize the energy output. The control system typically consists of a set of sensors, a flight controller, and a power management system. The sensors measure wind speed and direction, kite position, and tension in the tether. The flight controller uses this information to adjust the kite's flight trajectory, and the power management system regulates the generator's output to maintain a stable power supply.

Ground-generation AWE systems have several potential advantages over traditional wind turbines. AWE systems require less material to generate the same amount of energy as conventional wind turbines (Wilhelm, 2018) (Hagen et al., 2023). As a consequence of the low material use, the cost can be significantly lower (BVG Associates on behalf of Airborne wind Europe, 2022). In addition, AWE operates at altitudes where the wind resource is untapped. At these altitudes, there are more constant and stronger winds. On top of that, the operational altitude can be adjusted to harvest the best available wind resource (Bechtle et al., 2019).

Barriers can be found in the high complexity of the operation, lack of proven reliability, and limited experimental validation (Watson et al., 2019). Furthermore, the airspace regulations are not suited for AWE systems at the moment, although they are expected to be adjusted in the coming years (Salma & Schmehl, 2023).

Chapter 3

Literature Review

This chapter provides an overview of the literature on both considered technologies in terms of technical potential, economic potential, system integration, and ongoing research projects. Additionally, a section was dedicated to providing background into wind data and available databases as this is a fundamental aspect of modelling wind energy technologies.

3.1 Technical potential

To assess the potential of new technology at a large scale, it is essential to know what is technically possible and also what kind of development is expected in the near future. This section outlines a brief overview of the technical potential of floating wind turbines and AWE.

Floating wind turbines

It is common to assume that floating wind turbines will have the same wind turbines as conventional offshore wind (Gaertner et al., 2020). Therefore, the main research focus in technical potential computations for floating wind turbines is the suitable area. Sørensen and Larsen (2018) Identifies the suitable areas in the North Sea region based on a bathymetric analysis of the water depth. Global potential studies have also identified massive potential areas that can be unlocked by floating wind turbines (Bosch et al., 2018). Dupont et al. (2018) even stated that floating wind turbines are essential for policymakers to consider to unlock the potential for offshore wind globally. In considering the potential, all mentioned studies also analyzed the spacing between turbines in a wind farm configuration and the effects on generation output.

Floating wind turbines are expected to achieve significantly higher capacity factors than conventional offshore wind turbines because they can operate in areas with more constant and stronger winds. The pilot project Hywind Scotland confirmed this expectation by achieving the highest capacity factor of any offshore wind farm in the UK for three consecutive years. In the first two years of operation, an average capacity factor of 54% was reached, compared to 40% for average conventional offshore wind farms in the UK. A record of 57.1% throughout one year was achieved (Equinor, 2022).

Airborne wind energy systems

A fundamental paper on the concept of AWE was published in 1980 by Loyd (1980). In this study, a concept for computing the performance of a large-scale AWE system was laid out. The computation only focused on crosswind power extraction, neglecting the retraction phase of the kite. It can be seen as an idealized, upper limit for power extraction by a kite flying in crosswind motion. At that time AWE was purely conceptual, but over the past two decades, the idea has gained significant traction within the research community. Luchsinger (2013) extended the work of Loyd (1980) to describe the maximal power for a full pumping cycle. Recently, the focus for future upscaling of AWE systems is put on reference designs (van der Vlugt et al., 2019) and performance estimation (Ranneberg et al., 2018).

Trevisi et al. (2021) presents a configuration optimization for both ground-gen and fly-gen AWE systems where optimal designs are evaluated and compared. Additionally, global sensitivity analyses were done for both systems. The maximization of both Annual Energy production and economic profit was analyzed. The technical properties driving performance were identified. Additionally, it was shown that, because the kite design does not vary significantly for different wind conditions, larger kites can be used in regions with lower wind resource to achieve high capacity factors still (at slightly higher costs). In the profit maximization case, the highest capacity factor was 64% for fly-gen and 68% for a ground-gen system.

3.2 Economic potential

When evaluating the economic potential of a technology, the coupling between the technical potential and corresponding costs is made to see whether the benefits of a certain technology outweigh the costs. A brief overview of studies into the economic potential of both floating wind turbines and AWE systems is given in this section.

Floating wind turbines

Floating wind turbines are expected to behave in a similar way as conventional offshore wind turbines because the turbines will be virtually identical. Therefore, using the wind resource, the energy production can be estimated accurately, based on experience and knowledge of existing offshore wind turbines. The economic potential is therefore usually only described in terms of cost development and not in terms of the expected performance of the systems.

A recent expert elicitation predicted that the costs of wind energy, in general, will drop by 37-49 % by 2050 (Wiser et al., 2021). floating wind turbines are expected to achieve lower LCOE than current fixed-bottom offshore wind turbines by 2030 and to be in the same range as onshore and offshore wind turbines by 2050.
Maienza et al. (2022) provides a feasibility analysis methodology for specific floating offshore wind sites. The study applies this methodology to Italy as a case study. It showed that floating wind turbines are competitive with other energy sources (renewable and fossil). Wind resource was the main driver for the feasibility of a floating wind turbine project.
Ramachandran et al. (2022) reviews the various marine operations challenges on the path to commercialization of different types of floating wind turbines. Semi-submersible platforms were identified to have the most favorable properties from an Operation and maintenance, decommissioning, and installation perspective. A main challenge was found to be in support vessels that are required for installation and maintenance.

Airborne wind energy systems

In Heilmann and Houle (2013), an economic assessment of pumping kite generators is provided based on established methods for conventional wind energy conversion systems. The major factors that influence the economics of a pumping kite generator are outlined. The site characteristics, system characteristics, and rough cost estimation are computed with a simple set of input parameters. Using these inputs, the levelized costs of electricity (LCOE) are computed. Additionally, a sensitivity analysis of the impact of the input parameters is performed. The system was not very sensitive to a change in nominal power regarding capacity factor and even less regarding LCOE. In general, when the nominal power is too low, the system underutilizes its mechanical capabilities while a nominal power that is too high results in a lower capacity factor due to the system rarely achieving peak output. The kite size had a larger impact on the achieved capacity factor and LCOE with a similar trade-off for too small or too large kites. The most substantial effect was found when assessing the influence of the site parameters (wind resource). An increase in average wind speed has a strong impact on the LCOE, especially in the lower wind speed ranges. The lowest LCOE was 45 EUR/MWh for a wind site with 7 m/s at 50 m height.

When AWE started gaining more traction in the research world, the path toward implementing it on a large scale became the point of attention. Zillmann and Bechtle (2018) describes the emergence and economic dimension of AWE based on an inventarisation of technology status. The benefits and potential of AWE are emphasized and put in the context of global energy trends. AWE was identified as highly promising and potentially disruptive to the energy system due to the benefits in wind resource, cost, and environmental impact.

Kruijff and Ruiterkamp (2018) uses the Ampyx Power conceptual AWE design to lay out a roadmap towards deployment of AWE in the utility sector. The rationale behind major design choices is discussed after which a development plan is presented. The development plan that was laid out was firstly focused on a proof of concept of a safe and autonomous system. Next, for the first commercial products, the minimization of LCOE was prioritized. Finally, an increase in system sizes to maximize productivity will be dealt with. Different fixed wing models for each step are shown, leading up to the final projections of a 5 MW system design. The larger future designs are aimed at offshore applications.

By now, the potential benefits and barriers towards large-scale implementation have been mostly identified and the focus of new studies is shifted back to more specific AWE system implementations. Joshi et al. (2023) provides a concrete framework focused on creating value instead of minimizing cost. Because of the increasing fluctuation in electricity prices, the conventional approach of minimizing LCOE might not lead to the highest profits anymore. Electricity produced at low wind speeds, for example, is more valuable than electricity produced at high wind speeds. The trade-offs between designing a system that minimizes costs and one that maximizes value are determined. It was found that the system leading to the lowest LCOE was not always creating the highest revenue. Although this work is the outcome of only one specific case study, it shows the need to take design drivers into account aimed at capturing market value instead of solely reducing costs.

3.3 System integration

This report is about integrating floating wind turbines and AWE in an energy system and the potential benefits and trade-offs that come with it. While studies on the technical and economic potential are abundant, studies on actual implementation in the energy system, especially at a large scale, are scarce or lacking.

Floating wind turbines

Moore et al. (2018) investigated the potential of floating wind turbines in the UK using an energy system model. The outcomes showed that floating wind turbines can lower the total energy system costs, even though the LCOE is higher than for conventional wind turbines. The cause was identified to be better and more constant wind resource which led to more constant electricity production and thereby reduced the need for storage and balancing in the system compared to conventional offshore wind turbines.

An exploratory study into 2050 scenarios for the Danish energy system showed significant potential for floating wind turbines to produce high volumes of hydrogen (McKenna et al., 2021). Vanegas-Cantarero et al. (2022) provides a multi-criteria evaluation framework to assess the hypothetical deployment of floating wind turbine farms in Scotland and Portugal. When exclusively evaluating techno-economic potential, the study finds that floating wind turbines are already close to becoming competitive with other energy technologies. However, the study argues that emerging technologies can have significant benefits to society that can strengthen their business case but are not quantified in models that only consider techno-economic potential. Examples are the environmental impact and socio-economical benefits compared to other energy sources.

Airborne wind energy systems

Many studies on AWE in the energy mix are focused on the comparison to conventional wind turbines, the main competitor amongst renewable energy technologies. Lunney et al. (2017) assessed the potential of AWE as an addition to the electricity system in Northern Ireland by evaluating the technical and economical viability of deploying AWE and identifying optimal locations in terms of wind resource and geography. Significant potential was found for high-altitude wind technologies at economically viable costs.

Malz et al. (2020) made an elaborate comparison between drag-mode AWE systems and conventional wind turbines in terms of power production, variability, and geography. Performance indicators were the total annual power production, the Gini coefficient (a measure of variability), and the Pearson correlation coefficient between the two technologies. A strong correlation between AWE and conventional wind turbines was found, but in high wind shear areas the correlation decreased in favor of AWE. In Malz et al. (2022), the comparison of drag mode AWE to wind turbines was extended to integrating AWE in a cost-minimizing electricity system model for four European model regions at three-hour resolution. AWE was found to be of the most added value when applied in limited amounts and at poor wind sites. The total share of wind energy in the system was not increased by introducing AWE.

The combination with other technologies was investigated on a small scale by Reuchlin et al. (2023), focusing on AWE in a hybrid power plant system with solar energy, batteries, and a diesel generator. It was found that AWE can drive down the costs of a hybrid power plant significantly compared to conventional wind turbines. Another major advantage of AWE was found to be in the mobility and construction time of AWE systems compared to wind turbines, showing large potential in temporal and remote applications.

Even when a technology shows great technical and economic potential on paper, implementing a new wind energy technology also depends on other factors. Kamp et al. (2018) provides a study based on literature research and interviews with academic and industry experts that identifies barriers that block large-scale implementation of AWE and presents specific niche strategies to overcome these barriers. Lack of knowledge of the technology and lack of support and investment opportunities were identified as the main barriers to large-scale production and diffusion. Additionally, niche strategies that were found promising for AWE are focusing on specific favorable geographical areas, demonstration of the technology, and educating people on AWE.

3.4 Research projects

Multiple research projects have been set up or funded in recent years, dedicated to the emergence of floating wind turbines and AWE. The main ones are listed below.

JustWind4All: Horizon Europe project dedicated to addressing key challenges in effective and just governance of wind energy. Both floating wind turbines and AWE are assessed in the context of this project. This study was carried out within the JustWind4All project, as acknowledged in the abstract.

Floating offshore wind turbines

IEA task groups have been set up to create reference designs based on the expected development of floating wind turbines. Gaertner et al. (2020) defined a reference design for a future 15 MW offshore wind turbine, suited for both fixed-bottom and floating applications. Allen et al. (2020) specifies the characteristics of a floating platform designed for the reference turbine.

- **COREWIND:** This project aims at making floating wind turbines cost-competitive by designing floater concepts that are ready for grid connection. https://corewind.eu/
- **BLOW:** The Blow project is dedicated to designing floating wind turbines to allow offshore wind development in the Black Sea, which has deep waters preventing conventional offshore turbines from being constructed. https://cordis.europa.eu/project/id/101084323

Airborne Wind Energy

Following the growing attention for AWE, multiple research collaborations and projects have been set up in recent years. Currently, there are two ongoing projects dedicated to AWEthat were funded by European Union funds:

- **MERIDIONAL:** The MERIODIONAL project focuses on the technical aspects of AWE, optimizing performance, operation, and design of onshore and offshore AWE systems. https://meridional.eu/
- **INTERREG** Project dedicated to bringing utility-scale AWE systems closer to the market in North-West Europe (MegaAWE, 2021).

Additionally, the International Energy Agency (IEA) has set up a task group dedicated to AWE investigating the resource potential and markets, reference models, tools and metrics, safety and regulation, public acceptability, and AWE architectures (IEA task 48, 2021).

3.5 Literature gap

Studies on the technical and economic potential of both floating wind turbines and AWE are widely available, providing sufficient data to make assumptions on future development. However, system integration is lacking or only evaluated at a small scale. This study evaluates multiple countries in a large geographical area, for the first time assessing the impact of floating wind turbines and AWE in an energy system at a multi-country scale.

Floating wind turbines have been considered in an energy system at a country scale, but never at a multi-country scale. It is also the more mature technology of the two, having multi-MW scale projects in operation while AWE operates only at multi-kW scale so far. Due to the previous studies and practical implementations being in place, there is less uncertainty in the floating wind turbine assumptions compared to AWE.

For AWE, only onshore AWE has been studied in an energy system context, albeit at a single location or a very limited area and for electricity only. The potential of offshore AWE in a technical potential study or an energy system context has not been evaluated. This study evaluates AWE for the first time from a whole energy system perspective. Additionally, the combination of onshore and offshore AWE has not been studied before. This study will provide insight into the trade-offs and synergies in implementing both technologies in an energy system.

3.6 Wind data

An essential element in wind energy technology research is the wind resource data. The quality of wind databases is a constantly ongoing topic of research. The more accurate the wind data input, the more accurate the energy predictions of wind energy technologies become. To adequately model renewables production, high-resolution data is crucial, as well as properly documenting processing steps performed on the input data to enable others to understand and evaluate the outcomes correctly (Pfenninger, 2017a). An overview of different available databases and their underlying methodologies is outlined in this section.

3.6.1 Reanalysis

Most available databases for large geographical areas are based on reanalysis. Reanalysis combines historic weather forecasts, the latest weather models, and observations by assimilating the data. In essence, it is filling in the gaps between observations as accurately as possible to provide a picture of past weather and climate. The more data and validations available, the higher the resolution of a reanalysis database becomes. Reanalysis can provide historical weather data for large areas in a convenient way. However, validation is constantly needed because reanalysis can suffer from significant biases. Using the output of wind farms can provide a lot of information on validating reanalysis databases and if necessary, correct them (Staffell & Pfenninger, 2016). With a rapidly growing share of renewables in the energy mix, accurate weather data is becoming increasingly important and valuable.

ERA5 Wind Data

The most commonly used wind database for modelling large geographical areas is the ERA5 database, provided by the European Center for Medium-Range Weather Forecasts (ECMWF). The data is produced with a reanalysis method, using 4D variable assimilation and model forecasts of the ECMWF Integrated Forecast System (IFS). It consists of 137 vertical hybrid sigma/pressure (model) levels. The ERA5 dataset contains one hourly high-resolution realization of 31 x 31 km (European Centre for Medium-Range Weather Forecasts (ECMWF), 2023).

3.6.2 High altitude wind data

Compared to conventional wind turbines, AWE systems operate at significantly higher altitudes. Because of the high altitudes at which AWE systems operate, existing databases can be insufficient to model the wind profiles for these systems accurately. Most well-validated databases only consider altitudes of up to 100 m. There are databases available for high altitude which rely on reanalysis data, but validation is lacking. Studies have been done on verifying wind data at high altitudes and making more reliable approximations of the actual wind speeds at these altitudes. An overview of the methods currently being used or investigated is given below.

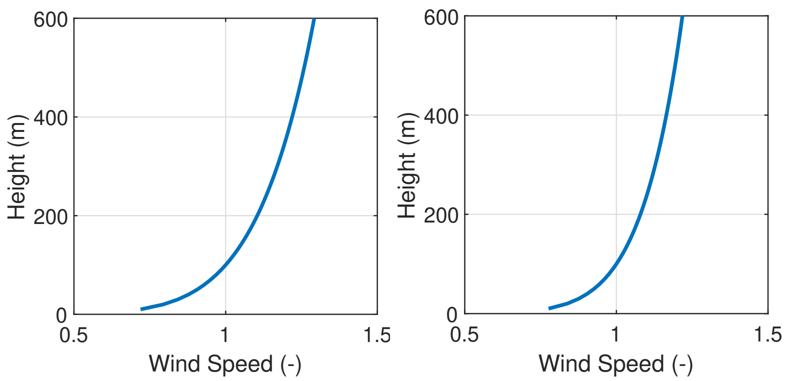
Wind profile

Most existing wind databases are based on the underlying assumption that the vertical profile of wind is logarithmic for low altitudes below 60 m and follows the so-called power law above this altitude. This is a good approximation for lower altitudes, but when wind speeds at surface layer height or above are considered, this method becomes insufficient (Bechtle et al., 2019). Higher in the atmosphere, the power law approach becomes inaccurate, and maximal wind speeds can occur below the ceiling height of AWE systems. Equation 3.1 and Equation 3.2 show the equation for a logarithmic and a power law wind profile respectively.

$$U_h = U(h_{ref})\frac{ln(\frac{h}{z_o})}{ln(\frac{h_{ref}}{z_o})} \tag{3.1}$$

$$U_h = U(h_{ref})(\frac{h}{h_{ref}})^a \tag{3.2}$$

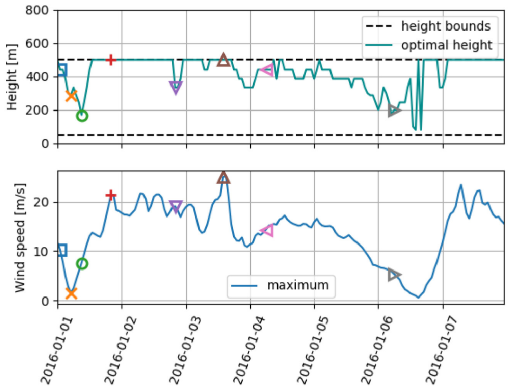
Where U is the wind speed, h is the altitude for which the windspeed is unknown, h_{ref} is a reference height for which the windspeed is known, z_o is the surface roughness length and α is the wind shear coefficient. Figure 3.1 shows wind profiles following the logarithmic and power law for onshore and offshore wind conditions, using empirically derived values for α that are commonly used.



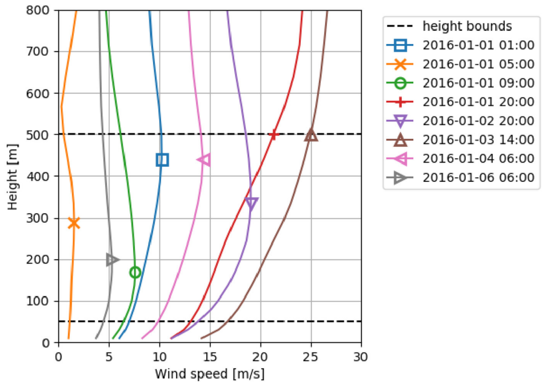
(a) Onshore wind profile, $\alpha = 0.143$ (b) Offshore wind profile, $\alpha = 0.11$

Figure 3.1: Two representative wind profiles using logarithmic (below 60 m) and power law (above 60 m). The wind speed is normalized relative to 100 m height.

Figure 3.2 shows observed wind profiles throughout one week for a location in the English Channel and the corresponding altitude at which the maximal wind speed occurs, considering a ceiling height of 500 m. It can be seen that, in practice, there is a wide range of possible wind profiles.



(a) Optimal harvesting height over time



(b) Exemplary vertical wind speed profiles

Figure 3.2: Optimal height analysis for one week at a location in the English Channel. The markers in the left figure correspond to the vertical wind speed profiles in the right figure (Bechtle et al., 2019).

High altitude wind resource analysis

Contrary to conventional wind turbines, AWE systems can vary their operational altitude. Bechtle et al. (2019) formulated a method using an existing model-level based ERA5 database (Hersbach et al., 2023) with hourly resolution in which the operational height could be varied according to the wind profile to extract maximal power. The available wind resource compared to a conventional wind turbine with a hub height of 100 m was assessed and is depicted in Figure 3.3

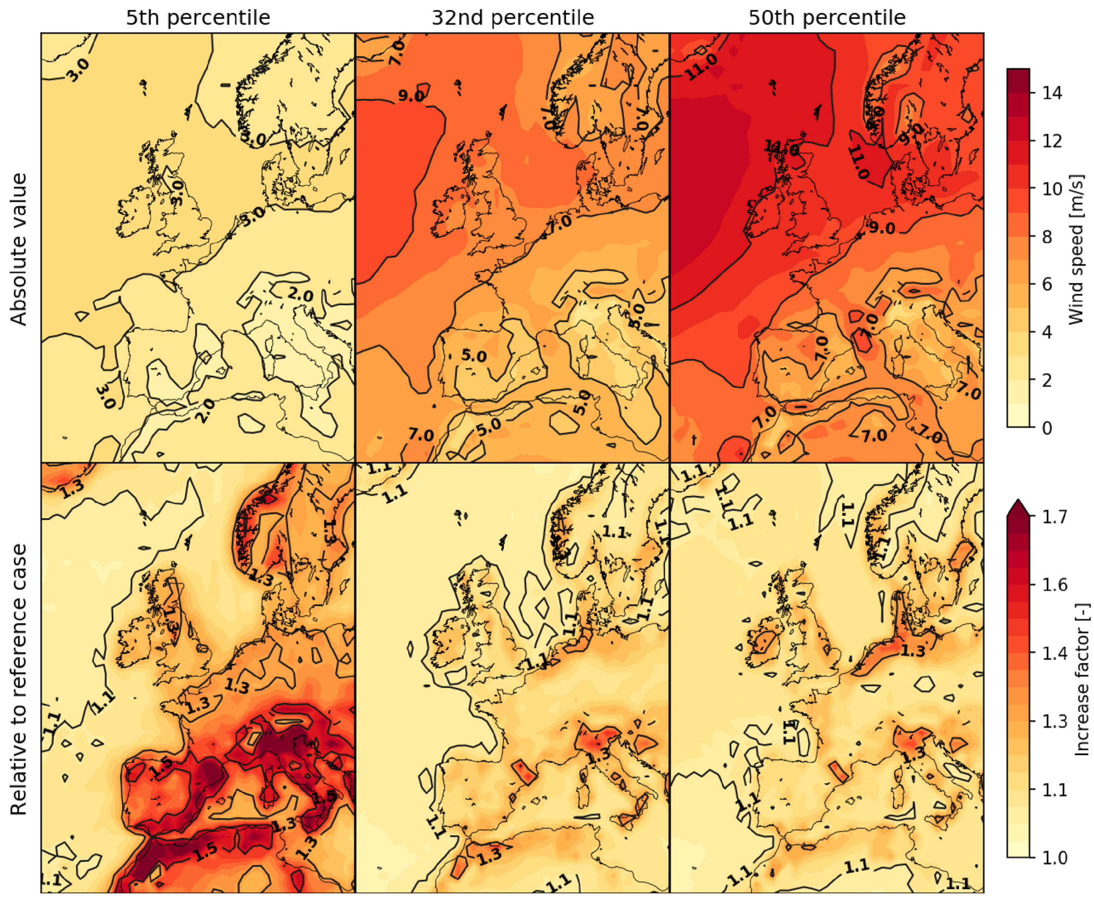


Figure 3.3: Wind resource for a 500 m ceiling height(top), and the relative increase with respect to a 100 m fixed-height (bottom) (Bechtle et al., 2019)

Wind profile clustering

Schelbergen et al. (2020) used K-means clustering to create all observed wind measurements into 10 representative profiles to simplify and save computational time. A statistical approach is used to determine how often each cluster is occurring at the examined test location. Based on this approach, a realistic simulation can be made of the power generation of a modelled AWE system. In this study, the Dutch Offshore Wind Atlas (Wijnant et al., 2019) was used, limiting the available area to the Netherlands.

Proceeding on the work of Bechtle et al. (2019) and Schelbergen et al. (2020), an open-source tool is developed for assessing the potential of AWE systems (Thimm et al., 2022) (Thimm, 2023). To obtain the annual energy production, a model is needed in which the full operation of a representative system is computed.

Chapter 4

Methods Offshore Wind Energy

This chapter provides the methods leading to representative future offshore wind turbine energy production, with an emphasis on floating wind turbines. First, the underlying inputs for the hourly capacity factor are given in Section 4.1. Second, the technology cost estimations are provided in Section 4.2. The spatial potential is treated in Section 4.3 and the wake and operational losses are described in Section 4.4.

4.1 Capacity factor

To determine the capacity factor, two inputs are needed: reliable wind data and the power curve of the system. For both, the methods leading to the final inputs are given in this section. The wind data is matched to the power curve to compute the hourly capacity factor.

4.1.1 Wind data

In this report, the publicly available www.renewables.ninja platform is used. Its underlying wind data is based on the NASA MERRA (Rienecker et al., 2011) and MERRA-2 (Molod et al., 2015) database. The obtained wind speeds are converted into power output using the Virtual Wind Farm (VWF) model, written by Ian Staffell (Staffell & Green, 2014). Additionally, the wind data is validated and bias-corrected using the realized output of existing wind farms (Staffell & Pfenninger, 2016).

Hub height

The wind speed that will be used is the wind speed at the expected hub height of future turbines. Based on the reference turbine used in this report, the expected future hub height was determined to be 150 m (Gaertner et al., 2020). The reference turbine characteristics are further described in Section 4.1.2.

4.1.2 Power curve

In offshore wind potential studies, it is common practice to use reference turbine designs, such as the NREL 5 MW reference turbine (Jonkman et al., 2009), which has become the standard reference design over the years. The size of offshore wind turbines is expected to keep increasing in the coming years. Therefore, larger reference designs have been published of up to 10 MW (Bak et al., 2013). A recent study by IEA task TCP task 37 entails a design of a 15 MW offshore wind reference turbine (Gaertner et al., 2020). This size aligns with recent press releases by industry leaders Vestas and Siemens Gamesa stating that the construction of 15 MW and 14 MW prototypes has started. Figure 4.1 shows the power curve from the 15 MW reference design. It is assumed by IEA task group 37 that the same 15 MW reference turbine will be used for future floating wind turbines. To achieve this, floating support structures must be upscaled compared to the currently available platforms (Allen et al., 2020) (Roach et al., 2023).

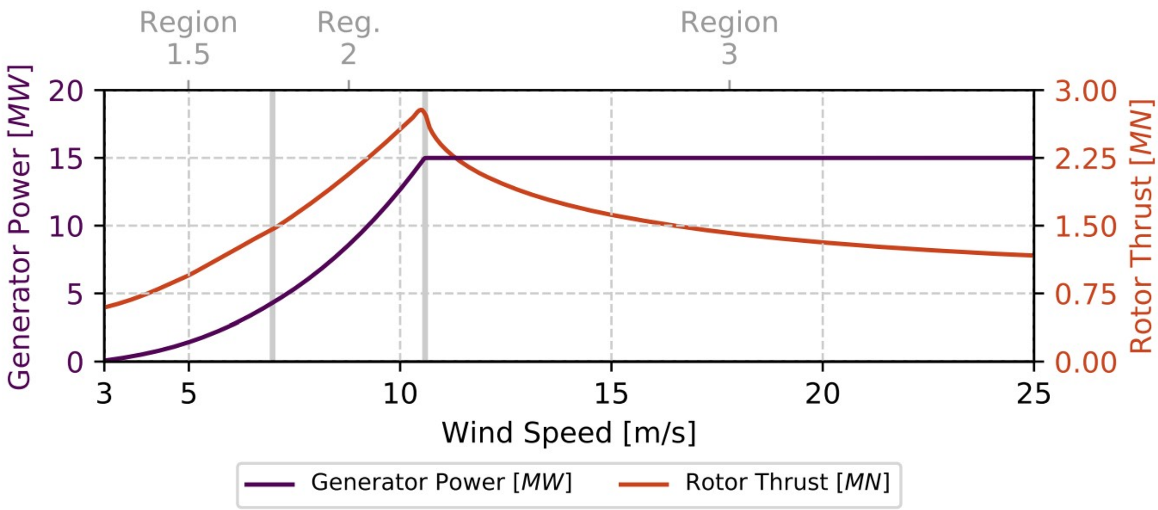


Figure 4.1: Power curve from the IEA 15 MW Offshore Reference Wind Turbine (Gaertner et al., 2020)

4.2 Technology costs

This section outlines the computation of technology costs for future offshore wind turbine energy. As final inputs for the Calliope framework, the CAPEX and OPEX projections are needed. For offshore wind turbines, there are many established, well-validated studies and databases available. Floating wind turbines are in an early stage of deployment and have more uncertainty in expected technology development compared to conventional offshore wind turbines. Therefore, more depth is provided for the floating wind turbines cost estimations.

Floating wind turbines

The technology learning curve for floating wind turbines can be largely based on the historical learning curve of conventional offshore wind turbines. Economic metrics and expectations are widely available in recent case studies in literature (Beiter et al., 2020)(Castro-Santos et al., 2020)(McKenna et al., 2021)(Maienza et al., 2022)(Martinez & Iglesias, 2022)(Vanegas-Cantarero et al., 2022)(Shields et al., 2022) and in industry (Equinor, 2022)(IRENA, 2016)(Energy Monitor, 2022). For the largest existing projects to date, rough cost approximations can be obtained (Hannon et al., 2019), as well as expected operation and maintenance models (Rinaldi et al., 2021).

National Renewable Energy Laboratory Annual Technology Baseline

As a guideline in this study, the data from NREL Annual Technology Baseline is used (NREL (National Renewable Energy Laboratory), 2022). This database is updated yearly, based on different governmental reports, industry developments and detailed studies, which are averaged. Additionally, a conservative, moderate and an advanced scenario are presented. It provides one of the most extensive and detailed databases for predicting the expected cost development of floating wind turbines. The data was found to be in line with the earlier mentioned studies in literature and industry outlook.

Danish Energy Agency Technology Data

In earlier studies using the same calliope framework that is the foundation of this study, a technology costs database by the Danish Energy Agency (DEA) was used (Danish Energy Agency, 2023). The DEA database is validated using existing projects and therefore does not entail floating wind turbine projections. In order to compute floating wind turbine costs projections based on the DEA database, the same ratio between conventional and floating wind as in the NREL database was used to extrapolate the cost projections for floating wind in the DEA framework.

Final model input

It was noted that the assumptions in the DEA and the NREL database are significantly different. Because of the high level of uncertainty on future predictions and the lack of validation for floating wind projects, it was decided to take the average of the two databases as input for floating wind cost predictions. For consistency, the same method was applied to conventional offshore wind. The final inputs are given in Table 4.1.

Table 4.1: Cost inputs FOWT and conventional offshore wind (fixed) (NREL (National Renewable Energy Laboratory), 2022)(Danish Energy Agency, 2023)

Technology	Source	2030 costs per MW		2050 costs per MW	
		Capex (MEUR)	Opex (kEUR)	Capex (MEUR)	Opex (kEUR)
Fixed Offshore Wind Turbine	NREL	2.75	87	2.33	71
Fixed Offshore Wind Turbine	DEA	1.80	39	1.64	33
Average		**2.28**	**63**	**1.99**	**52**
Floating Wind Turbine	NREL	4.04	71	3.46	59
Floating Wind Turbine	DEA	2.64	32	2.42	27
Average		**3.34**	**52**	**2.94**	**43**

4.3 Spatial potential

The main current constraint in deploying offshore wind turbines is the water depth. Current monopile-based structures only reach depths of 50-60 m. Another limiting factor on country scale is the available sea area that a country can use to exploit, the so-called Exclusive Economic Zone (EEZ). Within that region, there are many other factors to be taken into account when planning a wind farm. For example nature reserves, military zones, shipping lanes, coastal regions (visual impact) (Moore et al., 2018). Wind farms can also not be placed too far offshore because the costs of maintenance and connection to the electricity grid will become too high. A common assumption regarding water depth is that floating wind turbines can be placed at a maximum of 1000 m and fixed-bottom turbines can be installed at a maximum of 50-60 m (Bosch et al., 2018), (Moore et al., 2018).

Maximal capacity

Apart from the constraints mentioned above, there also has to be sufficient wind resource available to make the installation of a wind turbine economically viable. This report uses a study by ESMAP, a partnership by the Worldbank and 24 partners, which estimates offshore wind energy potentials per country (World Bank, 2019). The study takes the following constraints within the EEZ of each country:

- A maximal water depth of 50 m for fixed offshore wind.
- 50-1000 m water depth for floating wind farms
- A maximal distance to shore of 200 km.
- Minimal wind speed of 7 m/s at hub height (100 m)

It does not regard any other constraints within the EEZ of a country, making it an optimistic approach. The maximal energy density considered is 3 MW/km^2 or 4 MW/km^2, depending on average wind speed. In Appendix B the areas per country where floating and offshore wind could be deployed and at what scale are provided. The underlying wind maps used to compute the technical potential are from Global wind atlas version 3.0 (https://globalwindatlas.info) and are taken at 100 m altitude.

Physical limits

A common energy density for wind farms is 7-8 MW/km^2. However, this would not be feasible when the wind farm extends too far. When covering very large areas with a constant high energy density of wind turbines, the physical limits of extracting wind power from the atmosphere are achieved and the energy generation drops dramatically. An average energy density over large areas of 2 MW/km^2 can ensure sustainable long-term energy production (van der Zwaan & Taminiau, 2022). This limit is also considered in this report. To convert the ESMAP capacity potentials to land area, the average energy density in that study was 4 MW/km^2. Dividing by two to come to 2 MW/km^2 gives a conservative estimation, provided that the energy density in the ESMAP study is actually 3-4 MW/km^2. This leads to a maximal installed capacity that implicitly leaves room for taking spatial constraints such as nature reserves and clearance from the shoreline into account (because the energy density in wind farms is 7-8 MW/km^2, there has to be empty space in between them to stay below the average of 2 MW/km^2). The full table for converting technical potential in the ESMAP study to the inputs in this report can be found in Appendix D.1.

4.4 Wake and operational losses

When setting up wind turbines in a wind farm layout, usually a grid, there will be wake effects that influence the overall performance of this wind farm, compared to a single turbine. An average wake loss in the deployment of large-scale wind energy of 11.5%, corresponding to a unit efficiency of 88.5%, is taken into account (Bosch et al., 2018).

The availability for both floating and offshore wind turbines is assumed to be 97% (European Environment Agency, 2009). This assumption is widely used in literature when assessing the technical potential of wind turbines.

Chapter 5

Methods Airborne Wind Energy

In this chapter, the methods to compute representative future Airborne Wind Energy production are described. Section 5.1 outlines the workflow to achieve an hourly capacity factor for different representative AWE systems. First, the wind data input is discussed. Second, the modelling of the power curves is presented. In Section 5.2, the computation of the technology costs is explained, for both fixed wing and soft wing AWE systems. Section 5.3 describes the spatial potential for AWE technologies. The spacing of individual AWE systems in a wind farm configuration is regarded, as well as the land availability on a country scale. Finally, the wake and operational losses are determined in Section 5.4.

5.1 Capacity factor

This section describes the workflow that led to an hourly capacity factor for representative future AWE systems. To compute the hourly capacity factor, two inputs are needed. First, the method for gathering hourly wind speed data at operational altitude is described. Second, a representative power curve for both fixed wing and soft wing is created. In the end, the power curve is matched to the hourly wind speed to compute an hourly capacity factor.

5.1.1 Wind data

As described in the Section 3.6, high-altitude wind falls outside of the range for common formulas for wind profiles. Additionally, the uncertainty in reanalysis data was explained. The studies that were mentioned: Bechtle et al. (2019), Schelbergen et al. (2020), Thimm (2023) and Thimm et al. (2022), are trying to make a more suitable, reliable wind database for AWE systems specifically. These databases use AWE models as input to compute Annual Energy Production. It was not used in this study because it takes representative power curves as a starting point, which can not be used as input in these databases.

Extensively validated wind databases such as the Dutch Offshore Wind Atlas (Wijnant et al., 2019) would also lead to more reliable wind speeds at operational altitudes for AWE with a higher resolution. Because this database only applies to the Netherlands, it was not used in this study. Because of the large geographical area and the lack of well-validated available databases, the ERA5 database that was described in Chapter 3, which includes the operational altitudes for AWE systems, was chosen in this report.

Operational altitude

A major difference in using hourly wind databases for AWE systems compared to regular wind turbines is the fact that AWE systems are varying their operational height constantly whereas a regular wind turbine has a fixed hub height. In computing a capacity factor for regular wind turbines, the wind speed at hub height is taken as the average wind speed for the entire swept area of the wind turbine. For AWE, the wind speed would have to correspond to the operational altitude at any given moment to give an accurate approximation of the capacity factor at that exact moment. To approximate the average wind speed at operational altitude over a full flight pattern, the wind speed was chosen at a representative average operational altitude. This was linked to the existing altitude levels in the ERA5 database, leading to an altitude of 334 m, or 975 hPa air pressure.

Offshore AWE

A pertinent sub-set of the ERA5 data, interpolated to a regular latitude/longitude grid is available in the C3S Climate Data Store (CDS) and consists of 37 interpolated pressure levels. This interpolated dataset is not well calibrated to account for surface elevation. Therefore it is not representative at elevated land areas. However, the sub-set from the CDS provides faster access to the ERA5 data. Because it is representative over non-elevated areas, this dataset is only used for offshore AWE. The data was downloaded for a pressure level of 975 hPa, corresponding to the average operational altitude of 334 m (Hersbach et al., 2023).

Onshore AWE

For onshore AWE, the model-level-based ERA5 hourly data was used, which is archived in the ECMWF data archive (MARS) (Hersbach et al., 2017). The model-level-based ERA5 data considers the surface elevation but is slower to access. The data was downloaded for the model level corresponding to the same altitude of 334 m that was used for offshore AWE wind data.

5.1.2 Power curve

To determine the capacity factor of future AWE systems under given wind conditions, a representative power curve is needed. Since the current operational prototypes and commercial systems have scales of around 100 kW, estimating the upscaled characteristics of future AWE systems is prone to a high level of uncertainty. There are multiple approaches to determining the behavior of future, large-scale AWE systems.

First, the industry and research groups have expectations and ideas about the up-scaling of AWE technology and characteristics. Second, testing with existing prototypes can provide insight into the operational behavior and characteristics of a physical system. Different case studies that use existing AWE systems have been done. Thirdly, computational studies have been done in recent years and are still ongoing, into reference designs for AWE systems, which can be used as a standard to benchmark new studies and designs. A brief overview of these three approaches is given.

Industry outlook:

In 2021, the U.S. Airborne Wind Energy Workshop was held to gather stakeholders' perspectives on the status and potential of AWE systems to contribute to the U.S. Energy system. The workshop was hosted by the National Renewable Energy Laboratory (NREL) and included approximately 100 attendees from different backgrounds, related to AWE. A techno-economic analysis was done using input from different AWE players. To come up with a hypothetical power curve for 2030, a combination of soft wing (Faggiani & Schmehl, 2018), fixed wing (Eijkelhof et al., 2020) and fly-gen (Echeverri et al., 2020) (Vimalakanthan et al., 2018) were used and combined. The result is depicted in Figure 5.1 and includes both a 500 kW and a 5 MW power curve, as well as the well-known 5 MW reference design for a regular wind turbine (Jonkman et al., 2009). It is emphasized in the separately published workshop proceedings that the output comes with a great deal of uncertainty (Weber, Marquis, Lemke, et al., 2021). The workshop outcomes were used in a report to the U.S. Congress by the USA Department of Energy (Department of Energy USA & Energy Technologies Office Wind, 2021). This power curve was used in a potential study for Airborne Wind Energy in the Black Sea (Onea et al., 2022).

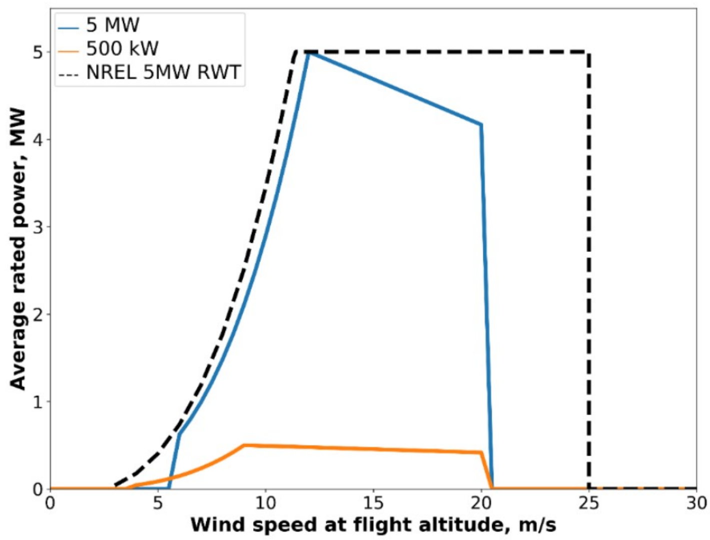


Figure 5.1: Power curve from NREL study into the potential of AWE (Weber, Marquis, Cooperman, et al., 2021)

Field studies:

Currently, the experimental data and field studies of larger scale systems entail mostly soft kite systems, with the Makani 600 kW (Larco & Echeverri, 2020) as an exemption. This is due to the fact that the costs of developing prototypes and testing for soft wing systems are lower than for fixed wing systems. The costs of soft wing kites are significantly lower compared to fixed wing aircrafts. Furthermore, soft wing kites are easy to replace and can withstand some impact when crashing, whereas a fixed wing system is highly fragile.

Several companies have launched, or are in the process of launching their first commercially available products. Examples of available ground generation soft wing kite systems are Kitepower Falcon (100 kW) (Kitepower, 2023) and SkySails SKS PN-14 (80-200 kW) (SkySails Group, 2022a).

Reference designs:

Similarly to reference designs for wind turbines, such as the NREL 5 MW reference wind turbine for offshore system development (Jonkman et al., 2009), there have been studies into a reference system for AWE systems. Such a reference system could help accelerate studies into AWE and also serve as a benchmark when testing new system designs or simulation methods. A reference design of a fly-gen system was created for the Makani M600 600 kW system (Echeverri et al., 2020) (Larco & Echeverri, 2020). For ground-generation AWE systems, there have been more reference design studies. A widely used model is based on a conceptual design, provided by Ampyx. Multiple studies into reference designs (Malz et al., 2019) and scaling effects of multi-MW systems (Sommerfeld et al., 2022) have been done based on this model.

More recently, a reference design called megAWES was created that consists of a simulation for a 3 MW ground generation fixed-wing system. Initially, the wing was modelled as a point mass (Eijkelhof et al., 2020), but recently this has been updated to a more realistic six degrees-of-freedom simulation (Eijkelhof & Schmehl, 2022).

The system operates in pumping cycles. For the modelling part, a quasi-static approach was used. In the first study (Eijkelhof et al., 2020), a power curve is given for a wind speed at 6m altitude. In the most recent study, the power curve is presented for trajectory height (Eijkelhof & Schmehl, 2022). The latter is shown in Figure 5.2. It can be noted that, after reaching maximal nominal power at a certain wind speed, the power output decreases at higher wind speeds. This is caused by the fact that the reel-in phase takes more energy for higher wind speeds, due to the larger resistance of the aircraft.

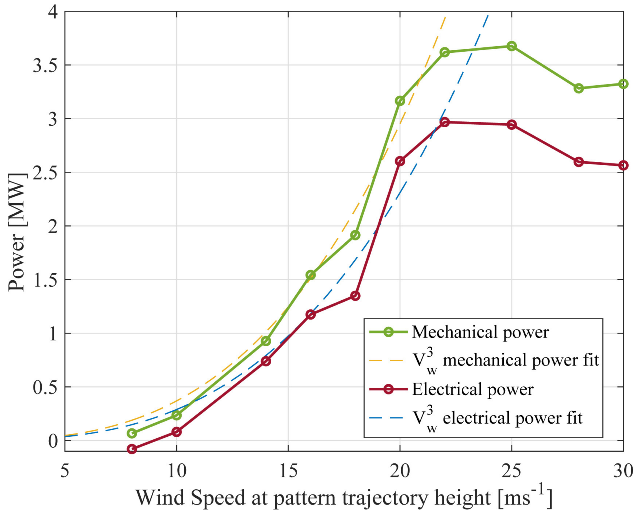


Figure 5.2: Mechanical and electrical power of a 3 MW reference system during pumping cycles (Eijkelhof & Schmehl, 2022)

Flight optimisation

Figure 5.3 shows mechanical power over a full pumping cycle at a maximal wind speed of 22 m/s, belonging to the power curve in Figure 5.2. It can be seen that the instantaneous mechanical power reaches up to 15 MW. This would imply a generator capacity matching that maximal power. It can also be noted that the flight behavior is very turbulent at this high wind speed, which can lead to operational difficulties and large wear and tear on the materials.

A significant part of the studies being done on the improvement of AWE systems performance concentrates on the optimization of control mechanisms, especially in modelling possible future prototypes. It has to be noted that the results in Figure 5.2 came from the first simulation runs with the model for unoptimized control. Improving flight characteristics for this particular model is the subject of ongoing research in which the control is improved significantly, resulting in less turbulent behavior and lower peaks in mechanical power.

In practice, a system without losses can not be achieved. But, optimizing control can cause major improvements in the system's performance. Given the ongoing research, growing industry, and recent publications, it can be expected that control in representative future designs has largely improved compared to currently available designs.

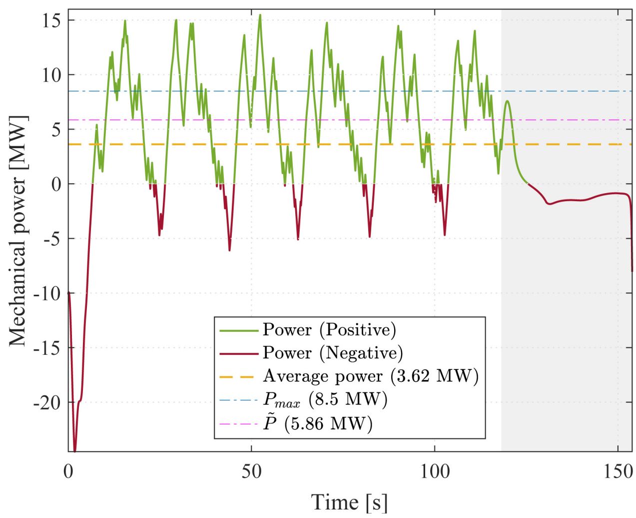


Figure 5.3: Mechanical power of a 3 MW reference system during pumping cycles (Eijkelhof & Schmehl, 2022)

Techno economic optimisation

When designing a full AWE system, the costs of the drivetrain components have to be taken into account. To facilitate the mechanical power in Figure 5.3, an oversized generator is needed. Additionally, and this is true for all AWE systems operating in pumping cycles, the oscillating power curve needs smoothing to be connected to an electricity grid. To do this, storage technology has to be included at the ground station (Joshi, von Terzi, et al., 2022). This creates a trade-off in the system design: when the components have too much overcapacity compared to the gain in energy output that comes with upscaling, the system becomes too expensive.

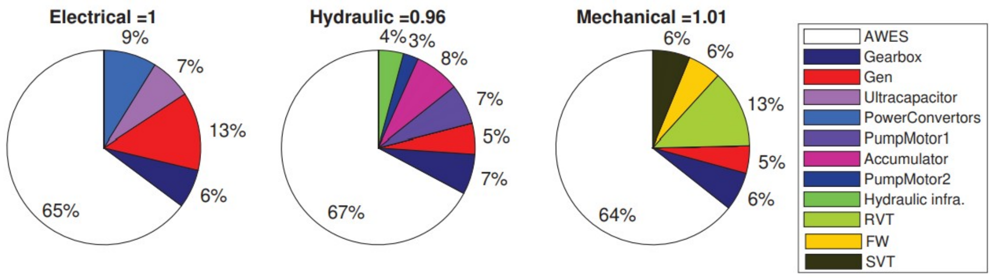


Figure 5.4: The share of drivetrain components in AWE design (Joshi, von Terzi, et al., 2022).

Final power curves

After inventarisation of industry outlook, field studies, reference designs, flight optimization, and consideration of the techno-economic optimization constraints, the representative power curves for future AWE systems were computed. The resulting power curves can be seen in Figure 5.5 with a comparison in Figure 5.5d. An explanation of how the power curves were computed is given below.

Fixed wing power curve

For a representative fixed wing AWE system, a simulation was used building on the models from earlier studies, but assuming idealized control. The power curve is computed using a quasi-steady model. The model is based on the steady-state flight dynamics of the kite and models the reel-out and the reel-in phases by discretizing the operation length into a number of elements. The model finds optimal operation set-points for a defined system to maximize the electrical cycle power. The relevant operational parameters are the reel-out length, pattern elevation angle, opening cone angle, starting pattern radius, maximum tether length, etc. This model was introduced in Bonnin (2020) and Joshi et al. (2023) and is a work in progress for a separate publication. Taking into consideration the turbulent behavior from Figure 5.3 and the techno-economic considerations from Section 5.2, it was decided to cap the system at 2.5 MW. This is just below the electrical power curve from Figure 5.2.

Based on the inputs of the model, a representative power curve and cost estimation are computed. The first computation was based on low costs, leading to a relatively cheap system. However, it was also noted that the resulting power curve could lead to underperformance compared to conventional wind turbines. Therefore, another power curve was computed with a lower cut-in wind speed and, more importantly, a lower rated wind speed. Adjusting these properties resulted in a higher system cost (larger kite), but also led to improved capacity factors. Both power curves are used in this report to investigate whether it pays off over the lifetime of both systems to invest more in a system that has better performance or to choose a low-cost design. This is a first rough approximation, but to fully answer this question, further and more elaborate investigation is needed in future work. The initial power curve from the script is called *Fixed wing 1* (Figure 5.5a)and the performance-optimized, more expensive system is called *Fixed wing 2* (Figure 5.5b).

Soft wing power curve

Soft wing kites are in the furthest stage of development of all AWE technologies at this moment. Multiple prototypes have been tested at a scale of around 100 kW and the first products are becoming commercially available. Because of this, there is actual operational data that can be used to determine the power curve of the systems. With these field studies as validation, realistic approximations can be made on future, upscaled systems. In this report, a 500 kW soft wing ground generation system is taken, based on test data from different field studies. The power curve comes from a computationally upscaled version of a smaller system, based on data from Kitepower. The power curve is depicted in Figure 5.5c.

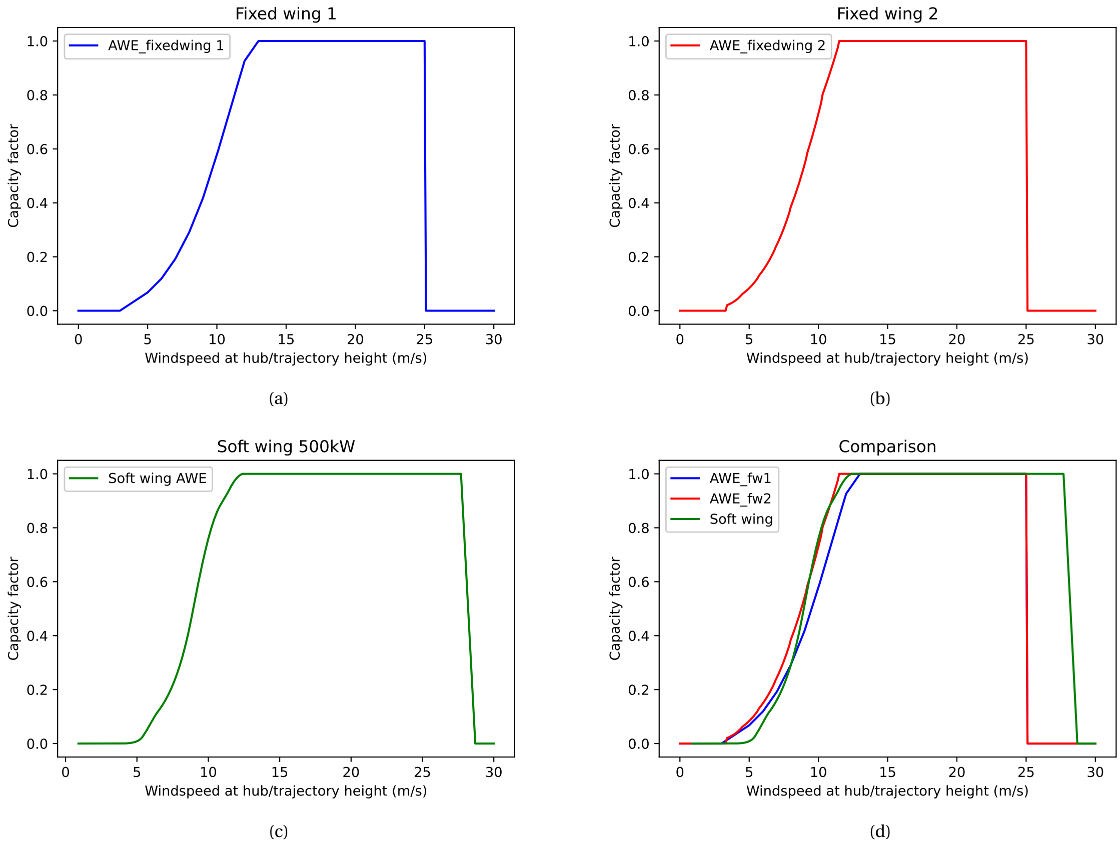


Figure 5.5: Overview of the used AWE power curves. Figure 5.5a shows a power curve for a 2.5 MW system that is optimized for costs. Figure 5.5b shows also a power curve for a 2.5 MW system, but then optimized for performance. Figure 5.5c depicts the power curve for the 500 kW soft wing system and in Figure 5.5d all power curves are plotted together for comparison.

5.2 Technology Costs

Because AWE is still in an early stage of development, it is difficult to give an accurate indication of how it will enter the market and at what price. There are still barriers that prevent the deployment of AWE, including autonomy, durability, and legislation (European Commission & Directorate-General for Research and Innovation, 2018). Another complication is the fact that there are many different techniques being developed, without a clear dominant technology (Watson et al., 2019). Each technique has different characteristics, leading to different LCOE and capacity factors.

In this report, a focus is put on ground-gen designs for AWE systems. The distinction is made between fixed and soft wing designs. Different studies have given rough estimates of the expected costs or levelized costs of electricity (LCOE) of AWE systems. However, for the Calliope framework, the CAPEX and OPEX costs are needed and the LCOE comes out due to the model simulation.

Soft wing

For soft wing systems, there are commercially available products on the market. This narrows the uncertainty in costs for future development and up-scaling of such systems. The most elaborate overview of the expected cost development comes from the sector itself. The publicly available report by BVG Associates on behalf of Airborne wind Europe (2022) gives cost estimations that were computed with inputs from major AWE companies. This serves as a foundation for the cost assumptions for soft wing AWE systems.

Fixed wing

For fixed wing systems, development is not as far as for soft wing systems yet, mainly due to the high costs of prototyping and testing. The cost data used in this report come from ongoing research by Joshi, Trevisi, et al. (2022) which is based on data obtained from companies, an extensive white paper on AWE by BVG Associates on behalf of Airborne wind Europe (2022) and public literature. Cost assumptions were found to extend only to 2030. Therefore, a learning curve was applied to compute cost assumptions for 2050. The learning curve was chosen conservatively at 3%.

Floating applications

As described earlier in this report, a significant potential of AWE lies offshore in floating applications. To compute the costs of such a system, the costs to build and maintain a floating platform have to be taken into account. The platform costs in this study are based on a project that was funded by the Dutch Ministry of Economic Affairs (RVO) and performed by a consortium with ECN (Energy Research Centre Netherlands), Marin (Maritime Research Institute Netherlands), Mocean Offshore and Ampyx Power. This project was formed to contribute to the technology development of a floating AWE system based on Ampyx Power's prototype AP4. Apart from the individual system, the possibilities and limitations of an AWE offshore wind farm were investigated. The study led to a conceptual design for a floating platform, which is taken as a reference for the costs of offshore AWE systems (van Hemert, 2017). The OPEX data in this study are computed for a relatively shallow, near-shore area of the North Sea. Therefore, these costs are taken as a reference for shallow water AWE (competing with conventional, fixed-bottom wind turbines). For deep water AWE, a 20% increase in platform CAPEX and OPEX is added.

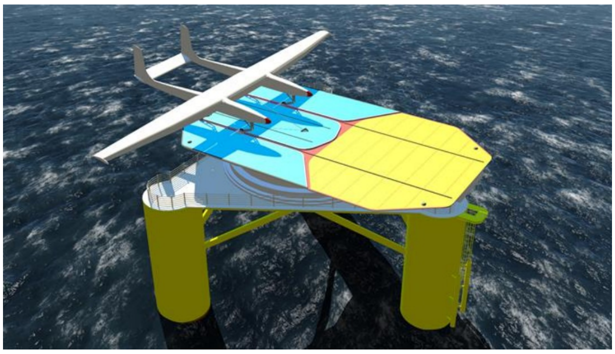


Figure 5.6: Conceptual design of a floating platform for a fixed wing AWE system (van Hemert, 2017).

5.3 Spatial potential

An overview of the spatial potential of AWE systems is given in this section. Focus points are the wind farm configurations of AWE and the land availability for the deployment of AWE technology.

5.3.1 Wind farm layout

To be integrated at a large scale in the energy system, AWE systems will have to be placed in a farm configuration, similarly to regular wind turbines. An important matter in the spacing between AWE systems is the safety factor. A very conservative estimate would be to leave a full circle, the size of the tether, of free space around the AWE system. An impression of the land requirement in this case is given in Figure 5.7. In the presented example, also a safety margin is added.

In practice, the wind will not come from different directions within the area that is needed to operate a wind farm. Therefore, studies have been done and are being done on increasing the packing density of AWE systems. A more realistic approach would be to leave only one tether length of distance between the AWE systems. Because the airborne devices will in theory always point in the same direction, there is still enough space in this configuration to ensure that two individual systems will never collide.

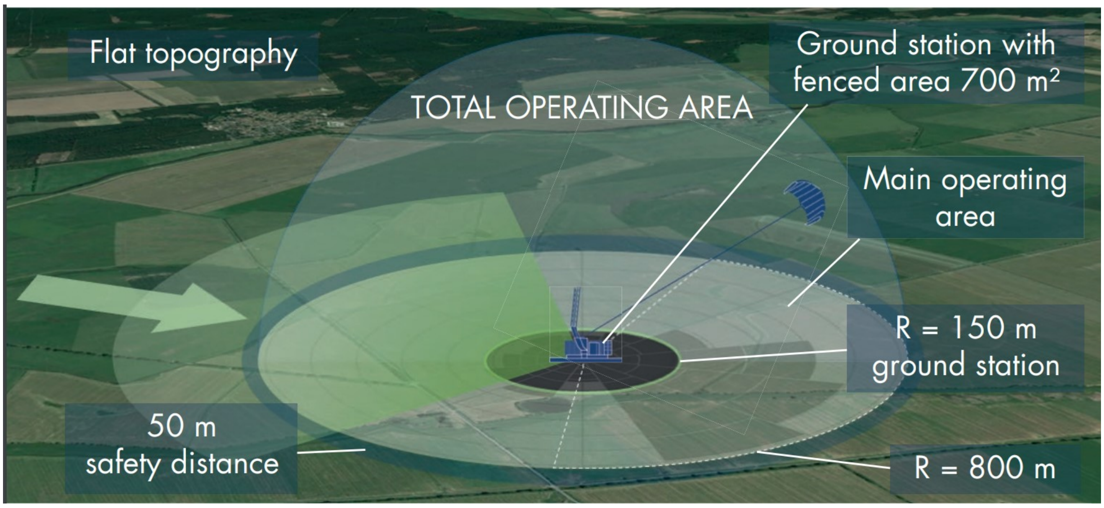


Figure 5.7: 3D visualisation of the operating area of an AWE system. In this case R is the tether length (800m) and a safety distance of 50m is taken into account(SkySails Group, 2022b)

Increasing the packing density above $1/L^2$ is the subject of ongoing research. There are operational limits in the flight path of the tethered devices, imposing a maximal and minimal flight angle. Additionally, optimisation in control can lead to the possibility of synchronized operation (Roque et al., 2020) and safety mechanisms that ensure the tethered device gets reeled in quickly when it exceeds the operational limits (Faggiani & Schmehl, 2018). Theoretically this means that the ground stations can be placed even closer, leading to an higher packing density.
Multiple studies have been done on this topic with limits varying from $1.2/L^2$ (Licitra, 2018) packing density to $3/L^2$ (Kruijff & Ruiterkamp, 2018). An example of what the layout of a wind farm could look like with high packing density is given in Figure 5.8.

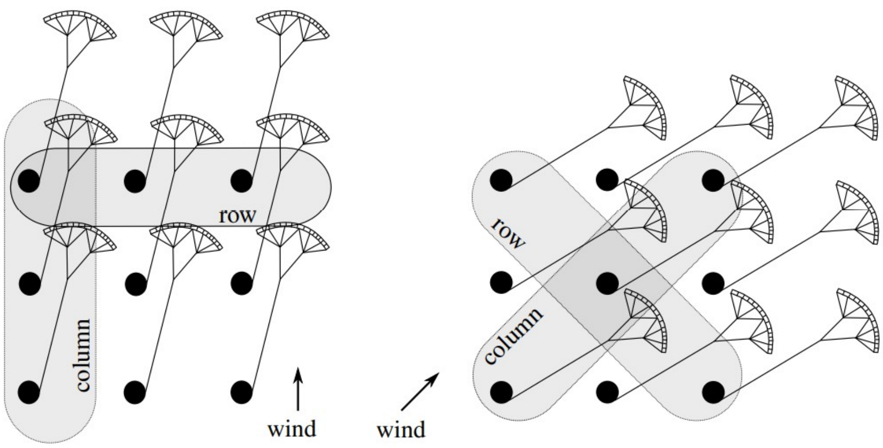


Figure 5.8: System layout for a packing density higher than $1/L^2$ for horizontal and diagonal inflow of the wind (Faggiani & Schmehl, 2018).

5.3.2 Land availability

It is assumed that the land availability for onshore AWE is equal to that of conventional onshore wind turbines. Safety margins and regulatory restrictions can cause the available land area for AWE to be smaller. On the other hand, AWE could turn out to be less problematic in terms of visual and noise impacts. Although in practice not all suitable areas for conventional onshore wind turbines will be suited for AWE and vice versa, there is too much uncertainty around this topic to make a more advanced assumption. The available land area data comes from the same workflow that was described earlier in Section 4.3.

For offshore applications, a similar assumption is made stating that floating AWE competes with both fixed-bottom wind and floating wind for the same areas. The computation of available land area for floating wind and for conventional offshore wind are described in Section 4.3 and final inputs can be found in Appendix D.1.

5.4 AWE Wake and operational losses

Packing multiple systems effectively requires a wind farm type layout, similar to what is being done for wind turbines. As described in Section 4.3, wake effects have to be taken into account. Up to date, physical test sites for multiple AWE systems at the same time have not been operated. Therefore, the only measurements of wake effects come from simulations.

In Figure 5.9, a top view of a modelled AWE wind farm layout with the wind coming perpendicular to the grid is given. Losses for ground-generation, lift mode systems are determined at: 18 % for a whole farm configuration with spacing of $2/L^2$. This is considering both wake losses and control losses due to sub-optimal control. Wake losses are 17% between the first and last row, therefore 8.5% on average over the whole system. Another study on the CFD approach that was used in Figure 5.9, is largely in line with these findings (Kaufman-Martin et al., 2022).

In computing the power curves, the anticipated optimization of control mechanisms in the future is considered. That same assumption is made in estimating the wake losses. Therefore, only the wake-induced losses were taken from Haas et al., 2022, which lead to a wake loss factor of 0.915 (8.5% wake losses).

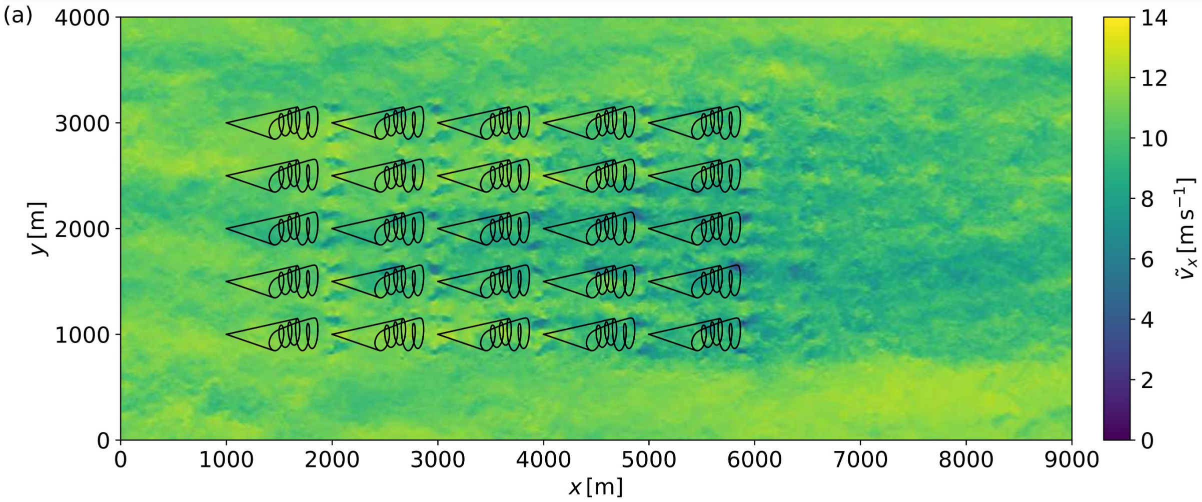


Figure 5.9: Top view of CFD modelling of wake effects for an AWE wind farm design (Haas et al., 2022).

Chapter 6

Modelling Approach

6.1 Calliope

The used model is built within the Calliope framework (Pfenninger & Pickering, 2018b). Calliope is an open-source modelling framework created to build energy systems at high spatial or temporal resolution. The model uses a cost-minimizing linear optimization and is designed to run easily and in a user-friendly way on high-performance clusters. It is especially suitable for using renewable resources data at high resolution.

Calliope allows users to model and analyze an energy system of arbitrary size. It consists of YAML and CSV files that define different technologies and their characteristics, locations, transmission links, resource potentials, energy demand, and other constraints. There are supply technologies, which can take a resource and turn it into a specific energy carrier. Transmission technologies allow energy of the same carrier to move from one location to the other. Conversion technologies can convert an energy carrier into another at a specified location. Demand technologies consume energy, removing it from the system. Storage technologies allow energy to be stored at a specific location. With all the inputs and constraints, an optimization problem is formulated and solved using open or commercial solvers (both are possible).

The Calliope framework was used in various studies such as an analysis of the power systems at national-scale in Great Britain (Pfenninger & Keirstead, 2015), investigating trade-offs for fully renewable energy scenarios in Europe (Tröndle et al., 2020) and research into different options to reach carbon neutrality in Europe (Pickering et al., 2022).

The framework is being developed in the open and accessible on GitHub (https://github.com/calliope-project/calliope (Pfenninger & Pickering, 2018a)). New releases are available on Zenodo (Pfenninger et al., 2023). Documentation can be found on https://www.callio.pe/.

6.1.1 North Sea Calliope

For this study, a sub-version of the Euro-Calliope model (Pickering et al., 2022) was used. It consists of a simplified energy system for the North Sea Region, containing the following countries: Norway, Sweden, Denmark, Germany, Netherlands, Belgium, Luxemburg, France, United Kingdom, and Ireland. Each country is represented by a single node and is linked to other countries corresponding to existing and planned electricity lines. For every individual country, the mix of available technologies, their maximal capacities, matching generation patterns and constraints is aggregated and averaged on a country scale. Transmission between different locations is allowed by using electricity cables or by import/export of synthetic fuels. Figure 6.1 shows the geographical area with the electricity grid that was used.

Renewable resource data

The underlying hourly capacity factors for onshore wind turbines and PV technologies come from an original modelling workflow that was set up by Tröndle et al. (2020). Apart from wind and PV, also hydropower energy and biogas plants were modelled. For both, the original inputs from Euro-Calliope were used, using underlying data from the European Joint Research Centre (Carlsson et al., 2014).

Sector-coupled

The model is regarding not only electricity demand and consumption but the complete energy demand of the considered region. It is sector-coupled, meaning all energy sectors are coupled in one system. Besides electricity, there are heat, hydrocarbon demand (synthetic fuels), and transport. Hydrocarbons can be derived from electricity or biofuels, also allowing them to be converted back into electricity. The direct applications will be mainly for heavy industry, which represents the largest part of current primary energy consumption.

Throughout the model, all demands can be met directly by electricity, but also by biofuels or waste heat when applicable. Also, different storage technologies such as hydrogen and battery storage are included in the model.

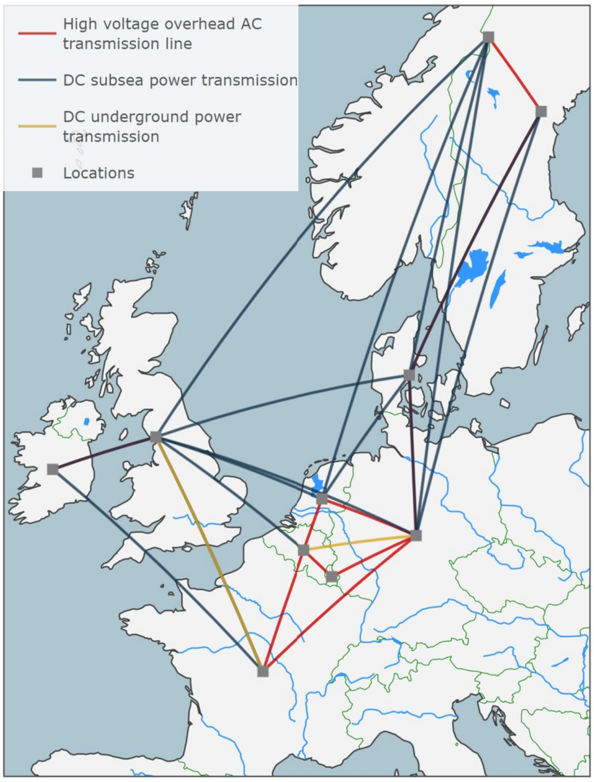


Figure 6.1: Representation of the North Sea Calliope electricity grid. The links are based on existing lines, planned connections, and connections that are already under construction

6.2 Data input

6.2.1 Country wide data

As explained in section 6.1, in the North Sea Calliope model, the energy system of the North Sea area is simplified to a grid with one node per country. This requires an average hourly capacity factor of energy generation technologies that is representative of the entire country. To accomplish this, a number of representative points are taken for each country in the model. The points are chosen in high-potential areas based on their average wind speeds and are spread throughout the available land area for each considered technology. The locations were identified based on the potential study by ESMAP (World Bank, 2019) and using Global wind atlas version 3.0 (https://globalwindatlas.info). A sensitivity analysis on this method can be found in Section 7.4

The coordinates for deep water AWE correspond to those of floating wind turbines and identically the coordinates for shallow water AWE are matched to the coordinates for conventional offshore wind turbines.

Once the locations were identified, the corresponding hourly wind data was extracted for each technology. As explained in Section 4.1, the data for offshore wind turbines and floating wind turbines comes from www.renewables.ninja for a hub height of 150m. The wind data for AWE comes from the ERA5 databases (European Centre for Medium-Range Weather Forecasts (ECMWF), 2023) as was further explained in Section 5.1. An example of the representative points for the Netherlands is given in Figure 6.2 The full list of coordinates and corresponding maps are given in Appendix B.1.

The obtained wind data for all technologies was averaged per country. Next, the wind data was matched to the corresponding power curves. This resulted in an hourly capacity factor per technology for each country.

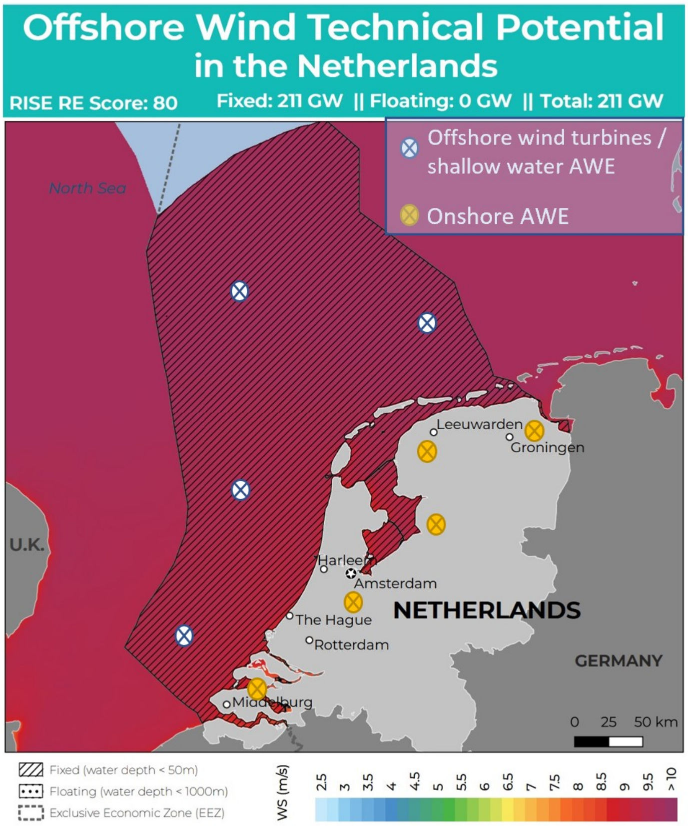


Figure 6.2: The locations where wind data was extracted for, using the renewables ninja (offshore wind turbines) and ERA5 database (offshore and onshore AWE). The underlying map comes from the ESMAP study (World Bank, 2019), the data points for the locations are overlayed.

6.2.2 Land availability

An important constraint in the North Sea Calliope model is land availability. In the original Euro-Calliope model, the land availability comes from an earlier study that used a GIS modelling approach to determine the absolute maximal land area that would be theoretically possible to utilize for wind or solar energy (Tröndle et al., 2019).

Offshore wind technologies

The methods used to compute the maximum installed capacity of offshore and floating wind turbines were described in Section 4.3. A group constraint was used in the North Sea Calliope model to ensure that the combined installed capacity of offshore wind turbines and shallow water AWE systems can not exceed the maximum. The same was done for floating wind turbines and deep water AWE systems. A list of these constraints can be found in Appendix D.1

Onshore technologies

For onshore renewables, the initial Euro-Calliope model distinguished two different land areas. One exclusively suited for onshore wind turbines and one where onshore wind turbines and PV technology compete for the same land. As explained in Section 5.3, the assumption was made in this study that AWE can be placed in the same locations as onshore wind turbines.

In reality, the theoretical maximal land area will never be utilized due to policy and social resistance. A more realistic assumption was made based on literature, which comes down to a maximum of 13.5 percent of the total theoretically available land area (McKenna et al., 2022). The resulting area per country can be found in Appendix D.1

6.2.3 Minimal installed capacities

At the moment, wind energy is being deployed at a rapid pace, with many planned projects or projects that are under construction. Following the Paris Agreement, countries have developed their renewable energy goals towards 2030. Some countries also formulated goals for 2050, when they want to become fully carbon neutral. Because of the installed capacity that is already in place and the many projects that are being developed or planned for the coming years, a realistic approximation for a future energy system in 2050 entails wind turbines, regardless of the innovation in other technologies. As a constraint in the modelling approach for this project, minimal installed capacities were imposed for conventional offshore wind turbines, floating wind turbines, and onshore wind turbines. As input the average between 2030 and 2050 goals was taken. When goals beyond 2030 were lacking or unclear, the 2030 goals were taken as a starting point. The inputs for the model are presented in Appendix D.1

6.2.4 Weather year

An important parameter that influences the configuration of the energy system and deployment of renewable energy sources is the weather year. Variable renewable energy technologies like wind and solar depend on the weather as a resource for their energy generation. The resource availability throughout a year and the correlation can have a significant impact on the required capacity and geographical spread of generation technologies. Ideally, the longer the timeframe, the better (Pfenninger, 2017b). In this study, 3 weather years were modelled based on the total system costs to test the effect the weather has on the outcomes and to evaluate the robustness of the results.

In total, 6 weather years of data were available. Three were selected: a 'bad' year, which led to the highest system costs, an 'average' year, and a 'good' year, corresponding to the lowest overall system costs. The highest system costs were found in 2013, 2014 represented an average year and 2015 led to the lowest system costs.

6.3 Scenarios

The interaction between different generation technologies makes it complicated to analyze individual trends of technologies. To isolate certain effects and explore the trade-offs in the deployment of floating wind turbines and Airborne Wind Energy in the energy system, scenarios were formulated. This section provides an overview of the three scenarios and the matching inputs.

6.3.1 Base case

The base case was determined to be at the initial cost assumptions for both the existing as emerging technologies. This means that for onshore wind turbines, PV, offshore wind turbines, and floating wind turbines, the average of NREL (National Renewable Energy Laboratory) (2022) and Danish Energy Agency (2023) assumptions for 2050 were used as input. For airborne wind Energy the computed costs assumptions from Section 5.2 were used. All the cost assumptions in the base case are given in Figure 6.3 All other technologies in the Calliope model are taken from the original Euro-Calliope model, which is based on numbers from Danish Energy Agency (2023). For reference, the cost assumptions for 2030 are provided in Appendix A.1 to give more context on technology development assumptions.

BASE CASE 2050:		
Technology	**CAPEX (10kEUR/MW)**	**OPEX (10kEUR/MW)**
Floating Offshore wind turbines	294.50	4.29
Offshore wind turbines	198.89	5.20
Onshore wind turbines	86.00	2.22
AWE soft wing	60.87	0.64
AWE shallow fw1	153.35	4.79
AWE shallow fw2	201.20	6.63
AWE deep fw1	169.66	5.42
AWE deep fw2	217.52	7.27
PV_openfield	46.88	1.07
PV_rooftop	63.75	0.93

Figure 6.3: Base case costs

6.3.2 Onshore AWE

To evaluate the trade-offs and effects of implementing onshore AWE, 11 scenarios were run for linearly varying costs of onshore AWE. The other technologies were kept constant at the base case level. The focus has been on technology costs ending up higher than assumed in the underlying study by BVG Associates on behalf of Airborne wind Europe (2022). The lower limit was set at 50 percent of onshore wind turbine costs which is relatively close to the base case and the upper limit was taken at 150 percent. This has two reasons: the underlying data assumes a rather optimistic development of costs and the timeline considered is 2050. The upper range of AWE costs evaluated can give insight into the nearer future where AWE is still more expensive. In Figure 6.4, the cost assumptions are visualized.

Because onshore AWE has to compete with PV and onshore wind turbines for the same land, the surface power density is an important driving factor for the potential. To assess the influence, different packing densities were considered of $1/L^2$, $2/L^2$ and $4/L^2$, corresponding to 2 MW/km^2, 4 MW/km^2 and 8 MW/km^2 respectively.

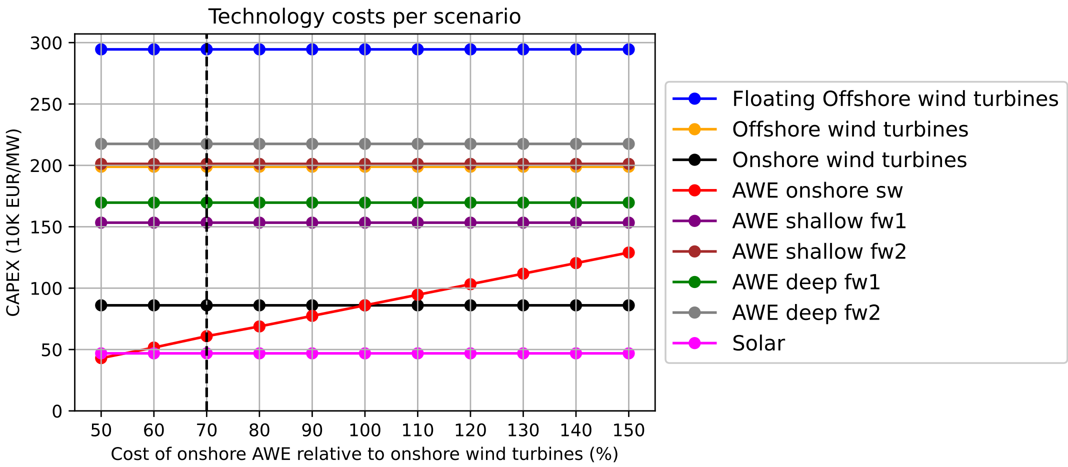


Figure 6.4: AWE onshore scenario costs. The dashed vertical line at 70% cost of AWE onshore relative to onshore wind turbines corresponds to the base case

6.3.3 Offshore AWE

A similar approach to the onshore AWE scenario was done to analyze the effects of offshore AWE in the energy mix. A slightly different cost variation was used. Instead of a linear variation, the AWE technologies are matched to their competitors: conventional offshore and floating wind turbines. In the first scenario, the costs of the most expensive floating AWE technology are matched to the cheapest rival: conventional offshore wind. In the last scenario, the cheapest floating AWE technology matches the most expensive competitor: floating wind turbines. A scaling factor was used in each scenario, which is applied to all floating AWE technologies. Figure 6.5 shows the costs for each scenario.

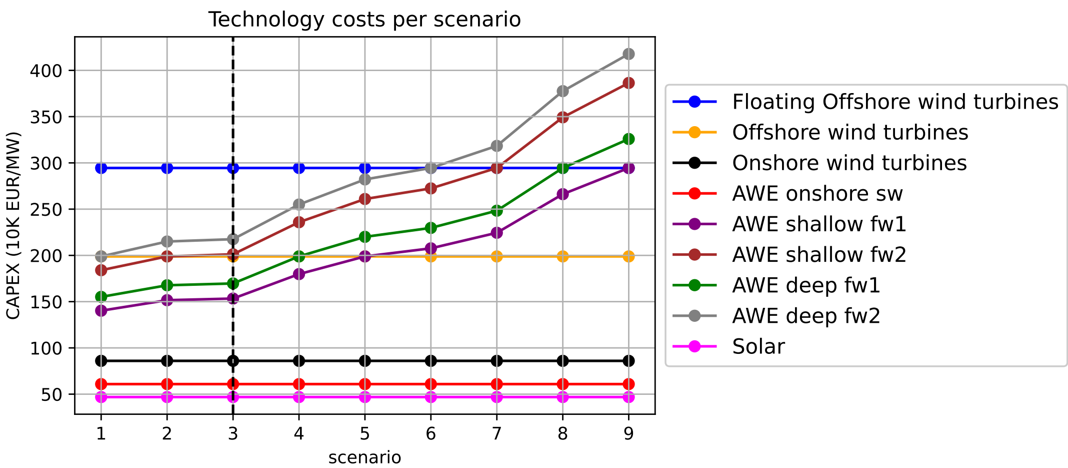


Figure 6.5: AWE offshore scenario costs. Scenario 3 corresponds to the base case and is indicated by a dashed line

6.3.4 Floating wind turbines

While AWE technology shows potential, the lack of large-scale installations and technological maturity makes it less viable than floating wind turbines for immediate deployment. Floating wind turbines are more mature and have already been proven to work at a multi-MW scale. Additionally, countries such as Great Britain and Norway have set targets for floating wind energy production towards 2030 already, making it realistic that this technology will enter the energy system in the foreseeable future. Therefore, this scenario exclusively evaluates the trade-offs associated with integrating floating wind turbines by isolating them from AWE technologies. This means that AWE is left out completely: both offshore and onshore. The costs of floating wind turbines are varied linearly, which is visualized in Figure 6.6.

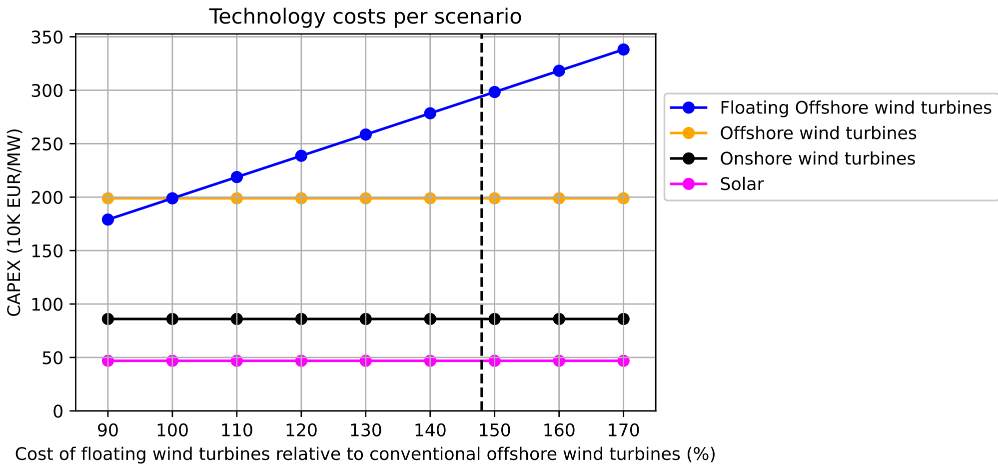


Figure 6.6: Floating offshore wind turbines scenario costs. The base case is indicated by a dashed line at floating wind costs of roughly 150% relative to conventional offshore wind turbines

6.3.5 Onshore vs. offshore renewables

The workflow, although significantly restricted, still has abundant land availability for onshore renewables. Because onshore renewables are generally cheaper than offshore renewables, the system will prefer to increase onshore capacity rather than offshore capacity when looking for a cost-optimal solution. However, in reality, most countries are aiming at offshore energy generation, because it has a higher social acceptance and therefore is easier to scale rapidly with less political sensitivity. This is also reflected in the policy goals of North Sea countries that were mentioned in Section 6.2.3. Therefore, a more stringent land availability constraint was imposed for the offshore AWE and floating wind scenarios. Consequently, the system is forced to install offshore capacity, which leads to an outcome that is more in line with the current expectations and policy goals. It also enables the identification of trade-offs between offshore wind technologies in a more realistic way. Inputs for land availability can be found in Appendix D.1.

Chapter 7

Results

This chapter provides the results of running the described scenarios for a full representative weather year at hourly resolution. The main findings and detailed analysis of the evaluated new technologies are presented for each set of scenarios individually.

First, the general outcomes that were found throughout all scenarios are described. Next, the outcomes for the AWE onshore scenarios are presented in Section 7.1. In Section 7.2, the outcomes of the AWE offshore scenarios are outlined, and Section 7.3 deals with the outcomes from the floating offshore wind turbine scenarios. At last, Section 7.4 deals with sensitivity analysis of the wind data inputs.

The results shown are for the weather year 2014, which was found to represent an 'average' year, as mentioned in Section 6.2.4. The outcomes for all weather years can be found in Appendix A.
Furthermore, for offshore AWE and floating wind scenarios in Section 7.2 and Section 7.3, the results shown are for the land-restricted configuration of the model that was described in Section 6.3.5.

Fixed wing AWE systems

Throughout all scenarios evaluated in this study, the 'high performance, high costs' fw2 AWE systems did not play a role in the energy system. The cheaper fw1 AWE systems were preferred by the model for both shallow water and deep water AWE deployment. To allow for a clearer analysis, the fw2 systems are not shown in the scenario results.

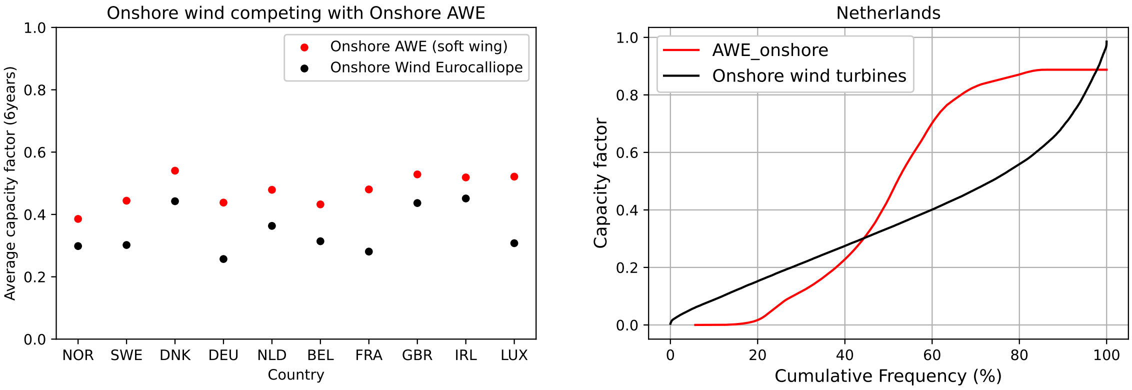
7.1 AWE onshore

In this section, the results for the onshore AWE scenarios are presented. First, the performance of AWE onshore is evaluated and compared to conventional onshore wind turbines. Next, the main limiting factor is identified. Lastly, the effects on the energy system of integrating onshore AWE are analyzed.

7.1.1 Onshore AWE significantly outperforms onshore wind turbines.

Figure 7.1a shows the average capacity factors of onshore AWE and onshore wind turbines that were used in the model over the considered time span, which is 2013-2018. When comparing the generation patterns of the onshore AWE system compared to onshore wind turbines, it can be seen that onshore AWE performs significantly better regarding average capacity factors. The largest difference can be found in France where AWE onshore systems have an average capacity factor of 48 percent compared to 28 percent for onshore wind turbines. The difference in performance also becomes clear when comparing the load-duration curves of both technologies, which is visualized in Figure 7.1b for the case of the Netherlands. This pattern is representative of the other countries as well, AWE onshore has significantly more hours with capacity factors above 50 %, but also more hours where the capacity factor is 0 due to the higher cut-in wind speed. Load duration curves for each individual country are given in Appendix C.

The generation profiles show that the available wind resource for AWE onshore differs considerably from onshore wind turbines. This is due to the difference in operational altitude. As seen in Section 3.6, the wind profiles for onshore wind conditions show a significant increase in wind resource at higher altitudes. As a result, AWE consistently outperforms onshore wind turbines. It can be found that onshore AWE and onshore wind turbines show a strong correlation in general, with Pearson correlation coefficients from 0.7 to 0.9. However, the difference in wind resource can lead to strong differences throughout the year, as shown in Figure 7.2.



(a) (b)

Figure 7.1: 6-Year average capacity factors for all countries for onshore AWE vs. the conventional onshore wind capacity factors from the Euro-Calliope model Figure 7.1a and load-duration curve for AWE onshore vs. conventional onshore wind in the Netherlands Figure 7.1b

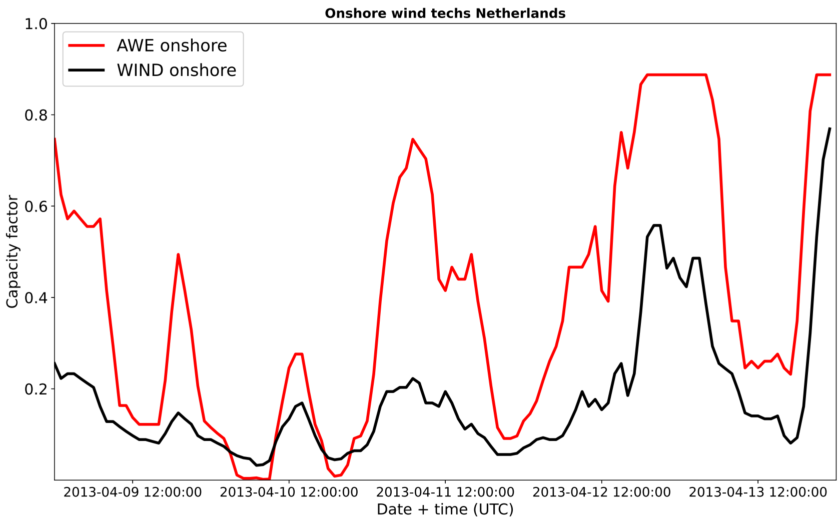


Figure 7.2: Onshore AWE generation profile vs. onshore wind turbines for five days in the Netherlands where the possible difference in performance at individual days is clearly visible

7.1.2 Spatial energy density is the main limiting factor for onshore AWE deployment

In Figure 7.3, the outcomes of all the onshore AWE scenarios are shown. The cost scenarios that were defined in Section 6.3 were run for spatial energy density of 2 MW/km^2, 4 MW/km^2 and 8 MW/km^2. The main result that stands out is that the implementation of AWE onshore increases dramatically with increasing spatial energy density. For an energy density of 2 MW/km^2, onshore wind turbines are the preferred onshore renewable energy technology over onshore AWE. When taking an energy density of 4 MW/km^2, onshore AWE and onshore wind turbines make up a similar part of the energy mix. When matching the spatial density of onshore wind turbines at 8 MW/km^2, it can be clearly seen that onshore AWE is the preferred technology, only to have less installed capacity than onshore wind turbines in the highest cost scenario.

Additionally, it can be noted that onshore AWE is included in the energy system for all the evaluated configurations, including the scenarios where the costs are 150 % of the costs of onshore wind turbines. In part this is because the cost variations were done for CAPEX only and not for OPEX, while the OPEX of AWE is substantially lower than for onshore wind turbines. To isolate the cost effects, an additional run was done where both the OPEX was matched exactly (Appendix A). In these scenarios, AWE is still included in each scenario configuration. At the same spatial energy density of onshore wind turbines (8MW/km^2), onshore AWE is the preferred technology of the two for costs reaching 110 % to 140 % of the costs of onshore wind turbines, depending on the weather year. This demonstrates the added value of onshore AWE purely in terms of performance. In reality, the OPEX of onshore AWE is expected to be significantly lower than for onshore wind turbines, as was assumed in the base case. Therefore, onshore AWE also has an additional cost benefit that is reflected in the results of Figure 7.3, with cross-over points at 130 and 140% for energy densities of 4 MW/km^2 and 8 MW/km^2 respectively.

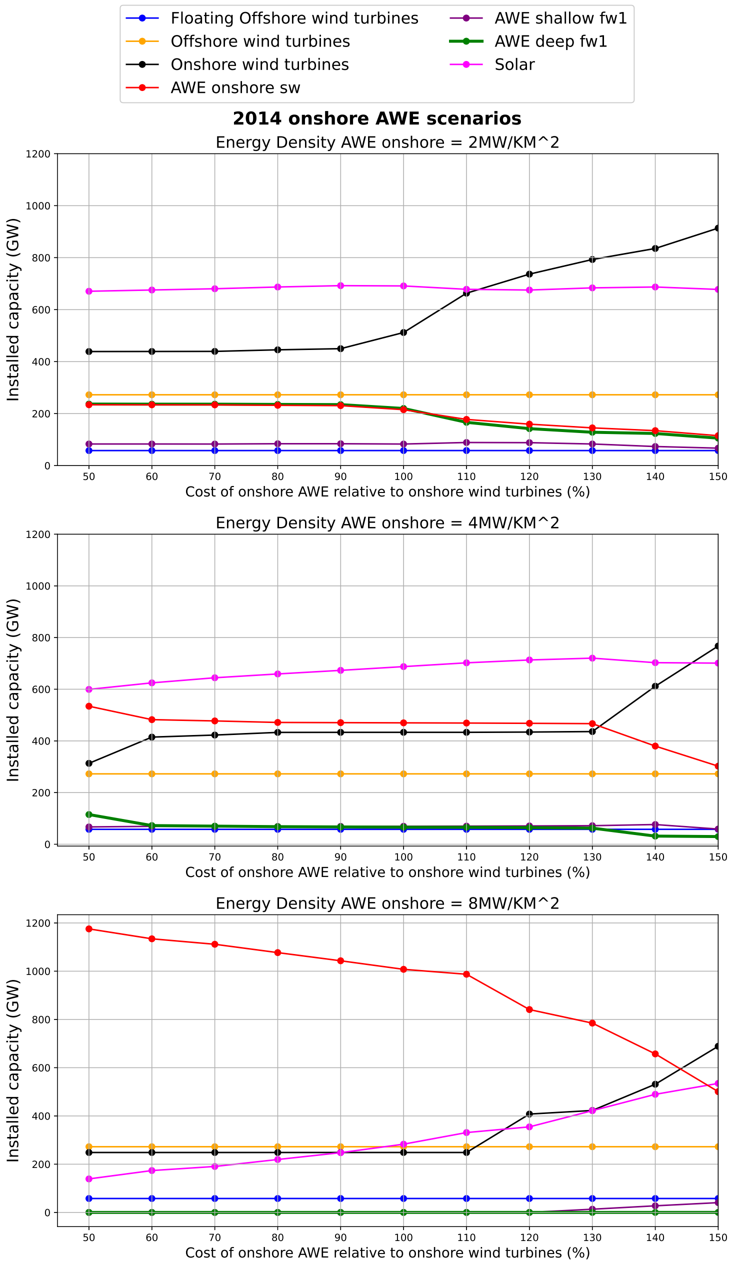
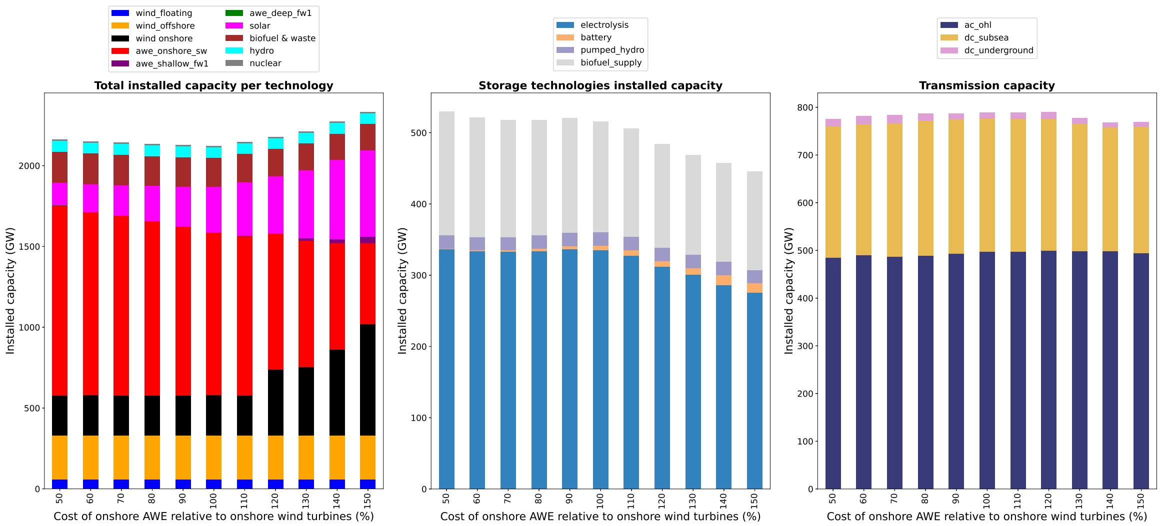


Figure 7.3: Installed capacity of the main supply technologies in the energy system throughout all evaluated scenarios for the three considered spatial energy densities, using the inputs that were given in Section 6.3.

7.1.3 System effects

AWE onshore has the potential to drive down the costs of the system substantially. Compared to the base case, increasing the spatial energy density resulted in a system cost reduction of 4% and 11% for 4 MW/km^2 and 8 MW/km^2 respectively. For the most optimistic cost scenario at 8 MW/km^2, the reduction was the largest at 14% compared to the base case. An overview of system costs for all scenarios can be found in Appendix A.2. Additionally, in all scenarios, onshore AWE has a significant role in the energy mix until cost levels are well above the base case assumption.

From Figure 7.4, it can be seen that, for the spatial energy density of 8 MW/km^2, onshore AWE drives down the total installed generation capacity, due to its high capacity factor. Increasing the share of AWE in the energy system leads to higher volumes of electrolysis and biofuel production, which are the main conversion techniques used for the long-term storage of surplus electricity. The increase in long-term storage comes from the seasonal effect in the generation pattern of onshore AWE, which has higher capacity factors in winter than in summer due to higher wind resource. When onshore AWE is phased out in the higher-cost scenarios, conventional onshore wind and solar energy take its place. This causes a more balanced energy generation throughout the year, resulting in lower long-term storage capacities. The increase in solar energy leads to a more diurnal generation pattern, which is then facilitated by an increase in battery capacity for short-term energy storage.



(a) (b) (c)

Figure 7.4: Stacked total installed capacity of all supply technologies in the system (Figure 7.4a), the installed capacities for the main conversion technologies (Figure 7.4b) and the installed transmission capacity (Figure 7.4c) for an onshore AWE spatial density of 8 MW/km^2.

7.2 AWE offshore

The outcomes of the offshore AWE scenarios are presented in this section. Firstly, the performance of offshore AWE compared to rivaling wind turbines technologies is considered. Subsequently, the main drivers and limitations are highlighted. Finally, the effects of integration in the energy system are evaluated.

7.2.1 Performance of offshore AWE has high similarity compared to offshore wind turbine technologies.

When analyzing the generation profiles for all offshore wind technologies considered, it stands out that the performance of competing technologies shows high similarity. As seen in Figure 7.5, the average capacity factor of deep water AWE and floating wind turbines is very similar, as well as for shallow water AWE compared to conventional offshore wind turbines. This is also reflected in the load duration curves in Figure 7.6, with the annotation that floating wind turbines slightly outperform deep water AWE. Additionally, the Pearson correlation factor between the competing technologies is above 0.9 for most countries (see Appendix E). Figure 7.7 gives an example of how correlated the generation patterns can be on certain days. This strong similarity originates in very little difference in wind resource at the respective operational altitudes of competing offshore wind turbines and AWE systems.

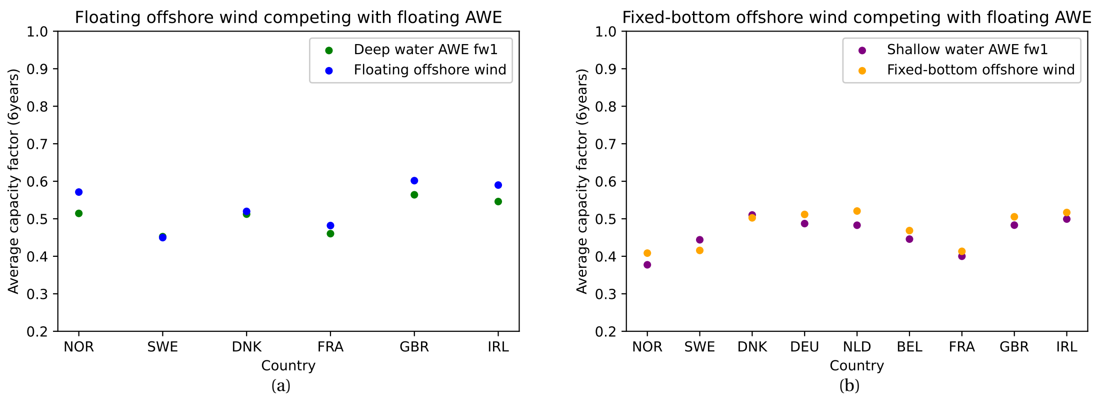


Figure 7.5: Overview of the 6-year average nationwide capacity factors of the competing wind energy technologies that were used as inputs for the North Sea Calliope model.Figure 7.5a displays floating wind turbines vs. floating AWE, Figure 7.5b shows fixed offshore wind turbines vs. floating AWE.

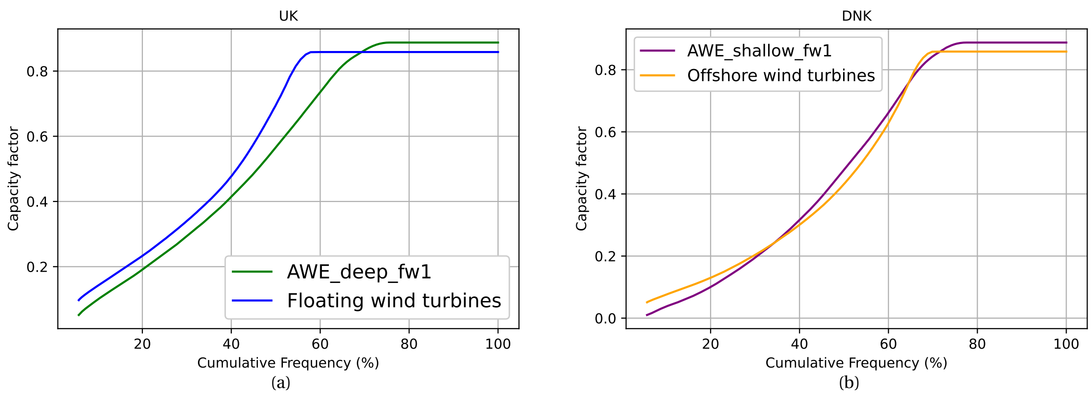


Figure 7.6: Load duration curves for floating wind vs. deep water AWE in the UK (Figure 7.6a) and Offshore wind turbines vs. shallow water AWE in Denmark (Figure 7.6b).

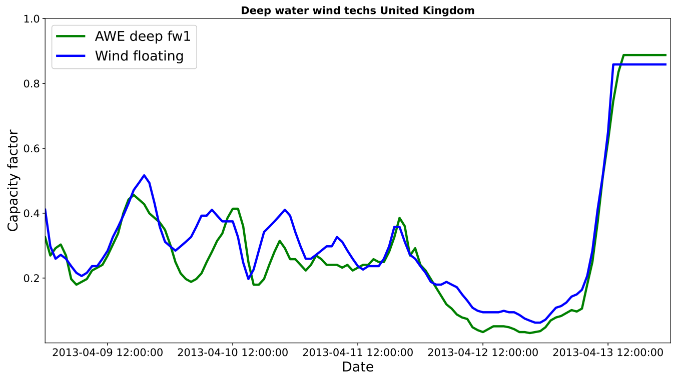


Figure 7.7: Representative generation patterns of deep water awe vs floating wind turbines over a period of five days in the United Kingdom.

7.2.2 Deployment of offshore AWE is mainly cost driven

Figure 7.8 shows the outcomes of the offshore AWE scenarios specified in Section 6.3 for all three different weather years. The deployment of offshore AWE compared to other offshore wind technologies is almost directly correlated with the cost variation compared to offshore wind turbines and floating wind turbines. In scenarios 1-3. for costs up until the base case level (scenario 3), both offshore AWE technologies are cheaper than competing offshore wind technologies, and offshore AWE gets deployed at a large scale, with a preference for deep water AWE. The cross-over points between deep water AWE and offshore wind turbines are either at scenario 4 or scenario 5, corresponding to the costs being the same or AWE being slightly more expensive respectively. Furthermore, the cross-over point between deep water AWE and floating wind turbines lies at scenario 7, when deep water AWE is still cheaper than floating wind turbines. This can be explained by the capacity factors of floating wind turbines being higher. In scenarios 8 and 9, Floating wind turbines have become the preferred technology over deep water AWE.

Considering the similarity in performance and correlation in generation patterns of offshore AWE and other offshore wind technologies, it can be concluded that whether offshore AWE is included in the energy system is almost entirely cost driven. In the base case, offshore AWE is cheaper and therefore preferred over rivaling offshore wind technologies. But also for cost levels above the base case, offshore AWE is deployed at a large scale due to higher capacity factors than conventional offshore wind turbines. When the cost levels of offshore AWE approach that of floating offshore wind turbines, it becomes clear that the higher capacity factors of floating wind turbines lead to them being the preferred technology over offshore AWE.

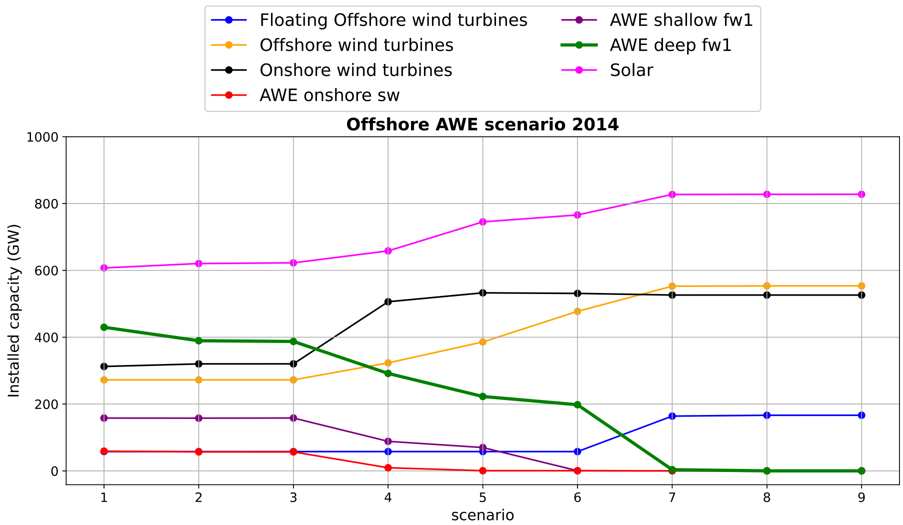


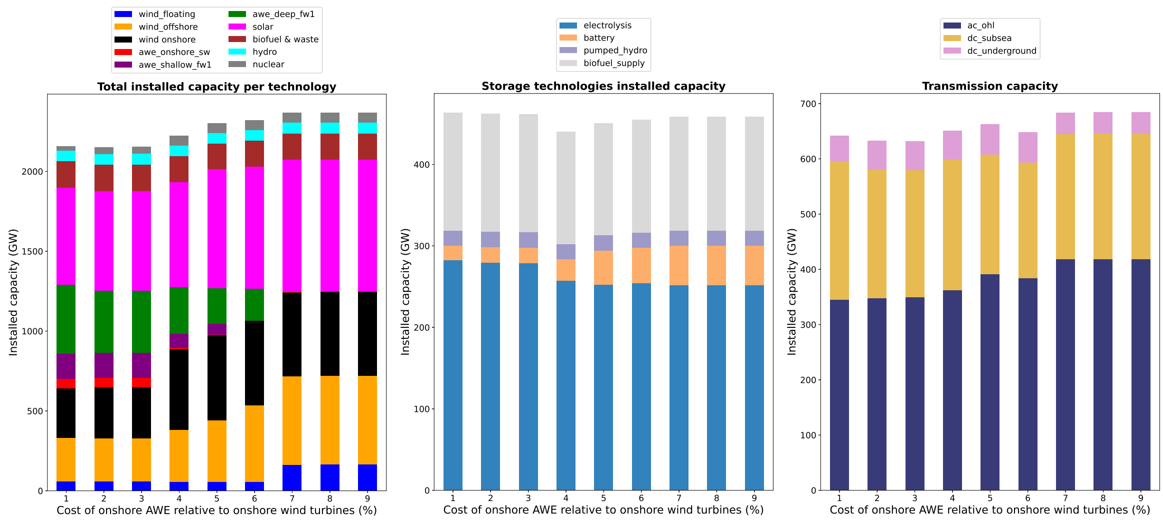
Figure 7.8: Installed capacity of the main supply technologies in the energy system throughout the evaluated scenarios for offshore AWE, using the inputs given in Section 6.3.

7.2.3 System effects

On a system scale, the capacity factor for deep-water technologies is higher than for shallow-water technologies. The results show that deep water AWE is the preferred technology over shallow water AWE on a system level, indicating that for the AWE systems, the difference in performance outweighs the fact that the deep water systems are more expensive. As seen in Appendix A.2, offshore AWE reduces the system costs in the base case scenario compared to scenarios without AWE although the differences are small.

The stacked total installed capacities, main conversion technologies, and transmission capacities are provided in Figure 7.9. Higher penetration of offshore AWE technologies in the energy system leads to a lower total installed capacity of generation technologies. Additionally, the electrolysis capacity increases due to the higher seasonality of AWE offshore (and other wind energy technologies). In the higher costs scenarios, offshore AWE becomes unfeasible and gets replaced by conventional offshore wind, onshore wind, floating wind, and a significant amount of solar energy. Hereby, the seasonality effects flatten out and instead, the need for short-term storage (batteries) rises due to the diurnal cycle of solar energy.

In terms of geographical spreading of the generation technologies, the deployment of offshore AWE is highly concentrated in the United Kingdom and Norway (see Appendix A.4), having the highest capacity factors. With the phasing out of offshore AWE as costs increase, the generation becomes more spread out with the replacing technologies. This effect is clearly visible in the transmission capacity, where the overland AC transmission increases drastically, implying more short-distance transmission.



(a) (b) (c)

Figure 7.9: Stacked total installed capacity of all supply technologies in the system (Figure 7.9a), the installed capacities for the main conversion technologies (Figure 7.9b) and the installed transmission capacity (Figure 7.9c).

7.3 Floating wind turbines

The results of the floating wind turbine scenarios, where AWE was left out of the model configuration, are presented in this section. Similarly to the previous results sections, the performance is analyzed first and compared to the main competing technology, which is conventional offshore wind in this case. Next, the trade-offs between floating and conventional offshore wind turbines are evaluated. Finally, the system effects are outlined.

7.3.1 Floating wind turbines can achieve higher capacity factors than fixed-bottom offshore wind turbines due to higher wind resource availability.

When comparing floating wind turbines to conventional offshore wind turbines, the difference in performance stands out. The same turbine characteristics were used but looking at Figure 7.10a, the difference in nationwide capacity factors is significant. In Sweden and Denmark, the difference is very small, but the other countries show a sizeable difference between floating and conventional wind turbines. The same is visible when comparing load duration curves for both technologies. The larger the difference in capacity factor, the poorer the correlation.

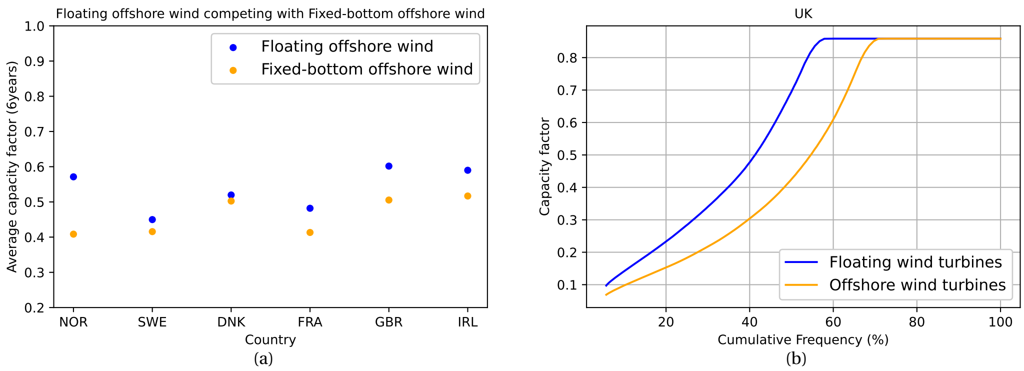


Figure 7.10: The 6-year average nationwide capacity factors for Floating wind vs. fixed-bottom offshore wind (Figure 7.10a) and the load duration curves for the United Kingdom (Figure 7.10b).

7.3.2 Floating wind turbines are attractive at considerably higher costs than fixed-bottom offshore wind turbines

Figure 7.11 shows the outcomes of the floating wind turbine scenarios specified in Section 6.3 for all three different weather years. From Figure 7.11 it can be seen that the cross-over point between floating wind turbines and offshore wind turbines lies roughly between 120% and 130% cost difference. Considering that the exact same turbine characteristics were taken for floating and conventional offshore wind, the difference in capacity factor is the driving factor in preference for floating wind turbines.

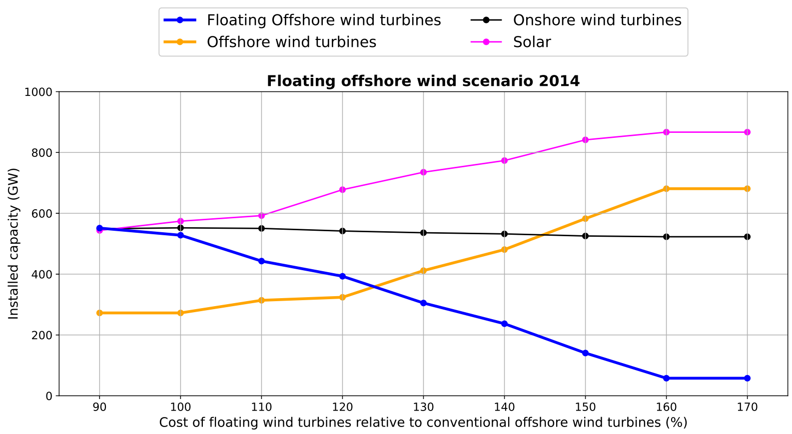
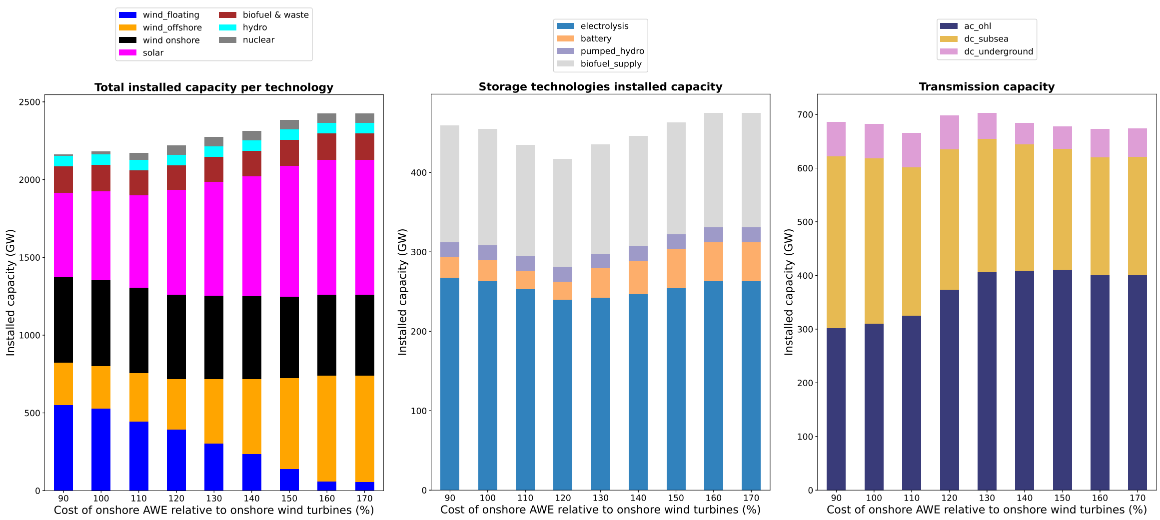


Figure 7.11: Installed capacity of the main supply technologies in the energy system throughout the evaluated scenarios for the three weather years, using the inputs that were given in Section 6.3.

7.3.3 System effects

Figure 7.12 shows the system dynamics for the different floating wind turbine scenarios. Integration of floating wind turbines in the energy system leads to a lower total installed capacity. The high capacity factors of floating wind turbines cause this. High shares of floating wind turbines also increase the long-term storage capacity in the system, mostly by electrolysis, due to the seasonal generation pattern. When phasing out floating wind turbines, the system replaces them with offshore wind and solar capacity. The shift makes the energy generation spread throughout the year and requires more short-term storage in the form of batteries, because of the diurnal cycle of solar energy. It can also be noted that the installed capacity of floating wind turbines is almost entirely in the UK and Norway (see Appendix A.4), leading to a more centralized electricity generation that requires more sub-sea transmission. Replacing floating wind with a mix of conventional offshore wind and solar leads to more local transmission via AC overhead land cables.

In terms of system costs, it can be seen from Appendix A.2 that increasing floating wind costs has a clear effect on the system costs in the scenarios with reduced onshore land availability, while the effects are minor in the base scenarios for onshore land availability. This is largely because, in the normal land availability scenarios, floating wind turbines will be replaced by cheaper onshore renewables when costs are increased. For reduced land availability, this option is not possible and floating wind turbines have to be replaced by conventional offshore wind turbines.



(a) (b) (c)

Figure 7.12: Stacked total installed capacity of all supply technologies in the system (Figure 7.12a), the installed capacities for the main conversion technologies (Figure 7.12b) and the installed transmission capacity (Figure 7.12c).

7.4 Sensitivity analysis

The capacity factors for wind technologies are determined by different wind databases and picking representative points. There are uncertainties in these assumptions that can have an effect on the outcomes.

Onshore AWE vs onshore wind turbines

For onshore AWE, the representative points were determined to compute a nationwide capacity factor, as described in Section 6.2, while the capacity factors from the original Euro-calliope model were used for onshore wind turbines. The method from the original Euro-calliope rests on averaging capacity factors based on actual wind farms and their locations. Thereby it gives a more realistic approximation of a nationwide capacity factor. However, when applying the same method as for onshore AWE to onshore wind turbines, matching the exact coordinates and using ERA5 data for a hub height of 136m, the difference in capacity factor is considerably more significant in most countries, as can be seen in Figure 7.13. This same difference could play out at a national scale when applying a similar method as the Euro-calliope model to onshore AWE. Due to the lack of existing AWE wind farms, this is impossible to date.

A conservative approach regarding the future performance of onshore AWE was preferred, because of the uncertainty in the development of the technology. Therefore, the Euro-Calliope capacity factors were utilized still, with the possibility of being too conservative on onshore AWE performance compared to onshore wind turbines. Further validation is needed to identify the difference in capacity factors with more certainty.

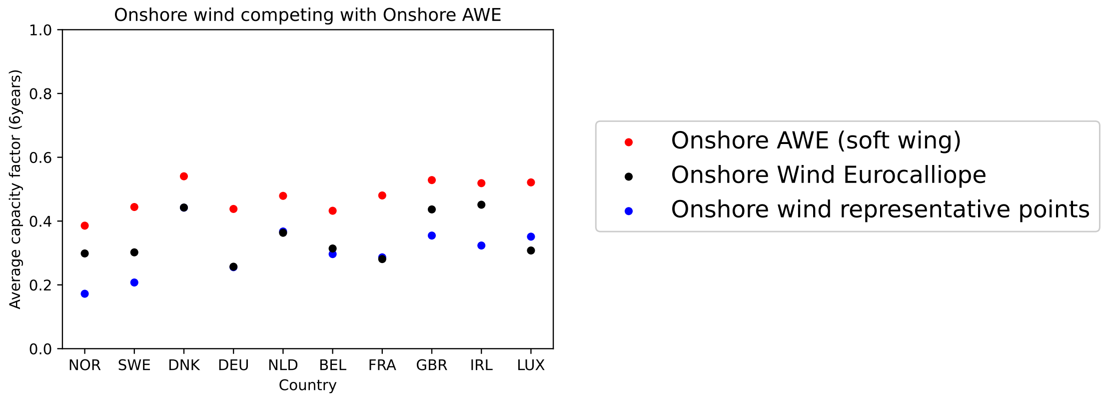


Figure 7.13: Capacity factors for onshore AWE, onshore wind using Euro-Calliope inputs and onshore wind using the same methodology as for onshore AWE (ERA5 data at representative points)

Renewables ninja data vs. ERA5 data

The wind data for Floating wind and offshore wind is taken from www.renewables.ninja while the wind data for offshore AWE comes from ERA5 (Hersbach et al., 2023). Besides being different databases, the data aggregation method also differs. The ERA5 database allows for a minimum of 4 points per request, making a grid of 0.25 x 0.25 degrees. The average of those points was taken as input for 1 representative point. For Renewables Ninja, only one specific coordinate was chosen per representative point. Consequently, the choice of the specific coordinate can influence the wind resource, especially when evaluating regions close to shore for conventional offshore wind where local differences can be considerable. For floating wind turbines, the divergence was found to be within 1% of the input capacity factors that were used, while for conventional offshore wind, it was found to be up to 3%. Because of the minor difference, the current inputs were determined to be sufficiently robust and representative.

Representative points

Which exact representative point is used influences the capacity factors that go into the model. It is difficult to determine the exact effect of this method. A more accurate approach would be to use a GIS-based method. However, comparing the inputs from this study to existing offshore wind potential studies in literature (Bosch et al., 2018) and the inputs from the original Euro-Calliope model, they were found to be comparable. Therefore, the current inputs form a realistic approximation of future nationwide capacity factors.
Another sensitivity is in the computation of the national capacity factor. In this study, the wind speed for the different representative points in a country is averaged first before it is matched to the power curve to determine the corresponding capacity factor. Computing the capacity factor first for each individual point and averaging that to come to a national capacity factor leads to a slight difference which was found to be within 2% of the capacity factor in either direction, depending on the country. This was considered to be within uncertainty margins and therefore the method was found to be robust.

Weather year

The results in this chapter all display the model outcomes where 2014 was used as input for the weather data. As discussed in Section 6.2.4 this was a good representation of an 'average' weather year. Although 2014 serves as a good representation, differences could be found between weather years. In general, the trade-offs that were identified were visible throughout the different weather years. However, for some individual technologies, the exact configurations showed variation for different weather years. As mentioned at the beginning of this chapter, scenario outcomes for all different weather years can be found in Appendix A.

Chapter 8

Discussion and conclusion

In Chapter 7, the main trade-offs in large-scale implementation for floating wind turbines and AWE were identified from a whole-energy system perspective. This chapter serves as interpretation and context for the findings that were presented. Additionally, the limitations of the applied methods and recommendations for future research are outlined. Finally, the main findings are summarized in the conclusion.

8.1 Discussion

In all scenarios regarding AWE, the cost variations were mostly focused on more pessimistic cost assumptions than the base case. In both onshore and offshore AWE scenarios, the base case demonstrated significant potential for the respective technologies. With the cross-over points being at higher AWE costs than expected by 2050, AWE has the perspective to become competitive at system scale in the imminent future, possibly as early as the 2030s. For offshore AWE a conservative learning rate of 3% was chosen from 2030 onwards. A higher learning rate can bring forward the moment at which offshore AWE becomes competitive.

The goal of the report was to identify trade-offs between emerging and existing wind energy technologies from a whole energy perspective based on cost assumptions for 2050. More aggressive cost reductions can make sure the cross-over points are achieved in the nearer future, possibly even in 2030.

From the analysis, it becomes clear that increasing the spatial energy density of onshore AWE has the most dramatic effect on system costs of all scenarios. The effect could be even stronger when onshore AWE turns out to be more preferable compared to onshore wind turbines than assumed in this study, as was described in Section 7.4. The costs at which onshore AWE becomes attractive compared to onshore wind turbines for the 8 MW/km^2 spatial energy density are not far off from the expected technology costs in 2030 (Appendix A). This implies that the major hurdle towards system integration is not the cost of an individual system but the spatial energy density at which multiple onshore AWE systems can be placed. There are two ways to achieve a higher energy density, either by increasing the capacity of an individual system or increasing the packing density.

The base assumptions in this report were taken conservatively for both system scale and packing density, due to the uncertainty in technology development. However, increasing the performance of systems is one of the main focus points of ongoing research, and systems with higher capacity have been presented in literature already. Similarly, raising packing densities has been the topic of research for some years, as was described in Section 5.3, with multiple studies considering packing densities of $2/L^2$ to $3/L^2$. Therefore, it is not unrealistic that higher spatial energy densities will be achieved in the future, although experimental validation is currently lacking.

Floating wind turbines were found to be attractive at base case costs, but showed a considerable increase in potential at lower costs. The cross-over point compared to offshore wind was found at lower costs than the base case while increasing costs above the base case led to the phasing out of floating wind turbines in the model outcomes. Consequently, there is little room for more negative cost developments than expected, but the potential remains significant.

Considering the long timeline towards 2050, there is uncertainty in the assumptions made for the costs and performance of future renewable energy technologies. In general, renewable energy costs tend to be significantly underestimated (Way et al., 2022), which could imply that the costs in this report are too conservative. This applies to existing renewable energy technologies such as onshore wind energy, fixed offshore wind energy, and solar energy. On the other hand, the technology assumptions for floating wind turbines and AWE in this report have not been proven to date, leading to uncertainty on whether the expected developments will be realized. Nevertheless, the evaluated scenarios show clear large-scale potential for onshore and offshore AWE through large differentiation in costs compared to the base case. For floating wind turbines the potential was found to be more sensitive to negative cost development with respect to the base case.

An important finding in the offshore scenarios is that the deployment of offshore wind technologies strongly depends on the onshore generation potential. Simultaneously, evaluating the system costs where land availability is heavily restricted compared to the normal scenarios, the system costs increase for reduced land availability stayed within 10% for all scenarios (see Appendix A.2). The model in this report only provides the cost-optimal solution, favoring onshore renewables for the assumptions made. However, the small differences in system costs coincide with the uncertainty margin of the cost assumptions made. When evaluating near-optimal solutions (Lombardi et al., 2020), offshore wind could already be preferred in certain configurations. This also means that when offshore wind cost reduction happens faster than assumed, the reality can be that offshore wind will be favored over onshore wind in the near future.

The difference in system costs (Appendix A.2) is small enough for non-cost factors to make offshore wind the preferred technology. Apart from costs, social acceptance and politics play a major role in favor of offshore wind compared to onshore wind. Public resistance towards onshore renewables is growing, especially in densely populated areas. The preference for offshore wind is already being reflected in the renewable energy goals that have been announced by the North Sea countries over the past years (Appendix D.1) and the agreements they closed on collaboration and merging of their offshore electricity networks.

Following the policy goals, investments, and public perception, it is very likely that offshore wind becomes the dominant wind energy technology. The expected growth in offshore wind deployment is already partly covered by the minimal installed capacity constraint that was explained in Section 6.2. A higher interest and preference towards offshore wind can accelerate the development of floating wind turbines strongly, due to the vast technical potential in areas where conventional offshore wind is not technically feasible. Huge investments are already going into floating wind turbine research with many leading offshore wind companies involved. Because of this, floating wind turbines could become cost-effective much sooner than anticipated in this study.

Besides the trade-offs between offshore and onshore renewables, also the geographical spreading that was found throughout the scenarios has to be noted. floating wind technologies were very concentrated in the UK and Norway for example, while France and Germany dominated solar. This comes from the fact that the model is only evaluating the cost-optimal solution. Marginal differences in costs can lead to these kinds of extremely centralized outcomes, while small variations can give drastically different results. In reality, it is highly unlikely to have such a large portion of generation capacity concentrated in a single country.

Finally, it has to be noted that the model simulations were run for the realization of a completely clean energy system in the North Sea region by 2050 which is a long way from the current situation. Additionally, the model considers the North Sea region as a completely self-sufficient energy system, while in reality it is integrated within the European energy network. The orders of magnitude in installed capacities that resulted from the model scenarios were in line with the policy goals towards 2050 that have been recently announced by the countries that were considered. However, the path toward such a clean energy system is surrounded by uncertainty regarding technological development, public opinion, political preference, geopolitical aspects, and many other components that can influence the energy transition in unforeseen ways.

8.1.1 Comparison to literature

The capacity factors for AWE systems considered in this study are in line with previous site-specific studies and reference models by Malz et al. (2020), Trevisi et al. (2021), Reuchlin et al. (2023). The difference between capacity factors for AWE compared to onshore wind turbines that was identified in these studies was expected to play out at a large scale as well when evaluating the difference in wind resource that was found by Bechtle et al. (2019). The timeline towards cost-competitiveness of AWE for both onshore and offshore applications corresponds to the general anticipation and outlook from the sector itself (Airborne Wind Europe, 2023). (BVG Associates on behalf of Airborne wind Europe, 2022).

For floating wind turbines, the capacity factors were in the same range as identified by Bosch et al. (2018). The cross-over points between conventional wind turbines and floating wind turbines were distinguished for larger differences in costs compared to Moore et al. (2018), in favor of floating wind turbines. Also, the higher wind resource potential for floating wind turbines is in line with Dupont et al. (2018) and Bosch et al. (2018), as well as expectations by the offshore wind industry (WindEurope, 2017) (Equinor, 2022).

Although uncertainty remains present in potential estimates for emerging technologies, the comparison to literature demonstrates that the inputs that were used for the energy system model in this study are realistic. AWE was not assessed from a whole-energy system perspective before, but the large-scale effects are comparable with earlier findings in studies for specific locations. For floating wind turbines, the higher wind resource availability and potential were widely described in literature and by the industry. The outcomes of this study confirm the potential of floating wind turbines in a large-scale energy system.

8.1.2 Limitations

There are certain limitations to the methods that were used and the assumptions that have been made in this study. The most important limitations have been listed below.

Cost-optimization models

This study used a cost-minimizing linear optimization model to assess the techno-economic potential of AWE and floating wind turbines. One of the known limitations of these types of models is that they only provide one outcome which is purely cost driven. There could be many viable solutions within a small margin of the cost-optimal solution that can be significantly more desirable and realistic from a societal perspective. Furthermore, cost-minimizing solutions do not represent the uncertainty in assumptions and sensitivity of the outcomes. To fully interpret the significance of cost-optimal solutions, it is important to be aware of the uncertainties involved with the inputs.

To assess the robustness of the results, taking into account the uncertainties of the inputs, near-optimal solutions can be valuable. As an addition to the Calliope framework, a methodology to do this was developed by Lombardi et al. (2020). This can provide insight into the uncertainty margin of the presented outcomes. Additionally, it enables modellers to find more realistic and socially desirable energy system configurations.

Validation of AWE performance

The performance of AWE was modelled using a power curve and wind data for an average operational altitude of an AWE system. An actual model that provides the annual energy production based on the flight operations throughout the year can provide a more realistic image of annual energy production. Such a method is being developed in the open-source AWERA tool by Thimm (2023) which is available on Github (Thimm et al., 2022). Additionally, experimental validation is vital to provide more certainty for future expectations.

Available area onshore

The available area was taken from the original Euro-Calliope model (Tröndle et al., 2020) and adjusted according to McKenna et al. (2021). The available area for onshore AWE was assumed to be the same as for onshore wind turbines. However, because of the identified difference in wind resource between AWE and conventional wind turbines, AWE could potentially open up new sites for wind energy that were not identified in the Euro-Calliope model. These potential new sites have not been taken into account in this report but could have an impact on the final outcomes. Especially when evaluating the reduced land availability scenarios, the importance of land availability for onshore renewables becomes very clear.

Physical limits wind extraction

A maximal extractable energy of 2 MW/km^2 was considered as the limit for offshore wind deployment based on literature. Although this is validated for wind turbines, AWE is not considered. Because AWE operates at a different altitude where the wind resource is high, the combination of AWE and wind turbines could lead to a higher feasible energy density. Additionally, the wake effects of AWE might turn out to be less. Therefore, 2 MW/km^2 can turn out to be too restrictive, but this has to be validated still.

8.1.3 Recommendations

Because of the exploratory nature of this research, many follow-up research topics were identified during the process. Some of the main recommendations for future research are listed in this chapter.

Country specific studies

To more accurately map the suitable sites for wind energy deployment and give a more detailed image of the nationwide capacity factors, national-scale studies are recommended. Using GIS methods and applying country-specific constraints, the technical potential can be more accurately mapped. Based on the outcomes of this study, it is recommendable to focus on the countries that demonstrated the highest potential for AWE or floating wind turbines.

Additional benefits

There are certain benefits for both new technologies that were not accounted for in the model. AWE requires less material than conventional wind turbines (Hagen et al., 2023) and floating applications in general have a potential advantage over offshore wind turbines regarding visual constraints and impact on marine life.

Noise and visual constraints AWE

There is much anticipation within the AWE research community and industry about the potential benefits AWE could have over wind turbines regarding noise and visual impact. Reduction of noise can lead to AWE being able to operate closer to residential areas. Due to the small swept area of the kites, the visual impact is in theory smaller compared to wind turbines. This could lead to more social acceptance of wind energy deployment near the coastline, in proximity to urban areas, or in natural reserves. Both topics are being researched at the moment.

Multicriteria evaluation

Many aspects are not visible when only costs are considered, but they do play a role in the decision-making process. For example societal acceptance, environmental impact, or complexity of supply chains. To capture many criteria, a multi-criteria analysis can be used. In such an approach, all criteria are listed and weighted according to their importance. This enables decision-makers to make more informed and better decisions. This kind of study can help to quantify the non-cost benefits of both technologies.

Other applications

For the assessment of this study, only new wind farm configurations of AWE systems are considered. One solution where AWE can bring value to the energy system is not discussed: the refitting of old monopile wind turbine foundations with AWE systems. When the lifetime of the monopile offshore wind turbines is exceeded, the foundations become too weak to support the forces of a wind turbine. AWE has a far lower overturning moment causing a lower load on the monopile. This way the monopile lifetime can be extended and all the existing electrical connections can be used, significantly driving down costs and environmental impact.

8.2 Conclusion

The goal of the research was to identify the main system-wide trade-offs in integrating AWE and floating wind turbines in a highly renewable future energy system for the North Sea region by 2050. To distinguish the trade-offs for each individual technology, scenarios were run where the effects of onshore AWE, offshore AWE, and floating wind turbines on the energy system were evaluated individually, based on 2050 costs and performance expectations

Onshore AWE performed significantly better than onshore wind turbines due to the higher wind resource availability at operational altitude. Consequently, onshore AWE reduces the overall installed capacity needed and can have a distinctly different generation pattern than onshore wind turbines. Furthermore, most scenarios considered were for higher onshore AWE costs than expected in the base case of this study, and still onshore AWE played a sizeable role. This indicates that onshore AWE can become economically viable before 2050, potentially even in the early 2030s. The main limiting factor was identified to be the spatial energy density. It was found that onshore AWE can substantially drive down the total system costs when the spatial energy density is increased.

When evaluating AWE offshore, it was noted that the performance and generation pattern of shallow water AWE and deep water AWE was almost identical compared to conventional offshore wind and floating wind respectively. Due to the high similarity, competitiveness was almost entirely driven by costs, which were assumed to be favorable for offshore AWE in most scenarios. At the system level, the deep water AWE systems were preferred over shallow water AWE because of the higher capacity factors. The preference for deep water AWE demonstrates that the difference in performance outweighs the increase in costs compared to shallow water AWE.

Floating wind turbines distinguished themselves from conventional offshore wind turbines by a clear increase in capacity factor. Floating wind turbines can operate in deeper waters that are usually further away from the shore, unlocking high wind resource areas. As a result, the technology was found to be preferred at costs of 120-130% relative to conventional offshore wind turbines, reducing the overall installed capacity required and the costs of the system.

On top of the individual technology effects, a main system-level trade-off was found to be between offshore wind deployment and the onshore technical potential. Offshore wind technologies were only deployed when onshore land availability was heavily restricted. However, the difference in system costs was within the uncertainty margins of the cost and performance assumptions of the considered technologies. Non-cost factors are expected to make offshore wind the preferred technology, which is already reflected in the policy goals and investments being done in most North Sea countries.

This report results from an exploratory study into the potential benefits of integrating AWE and floating wind turbines in a highly renewable energy system, laying a foundation for future research. The results show significant techno-economic potential for both technologies, each having its individual characteristics. The key findings in this report were found to be in line with expectations based on earlier studies and anticipation within the industry. However, follow-up research is necessary to validate the outcomes of this study further and to provide more detail and context.

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I
Appendix

Appendix A

Scenarios

This appendix chapter shows multiple scenario outcomes that were not included in the main text.

A.1 Costs 2030

In Figure A.1 the cost assumptions for 2030 are presented. These cost assumptions were used as a starting point to determine the 2050 cost assumptions for offshore AWE. The 2030 costs were not used for scenario runs in this study because the most critical trade-offs were already identified in the 2050 scenarios. However, it serves as context to show how far from the cross-over points in the 2050 scenarios the 2030 expectations are.

BASE CASE 2030, average NREL and DEA		
Technology	**CAPEX (10kEUR/MW)**	**OPEX (10kEUR/MW)**
Floating Offshore wind turbines	334.36	5.11
Offshore wind turbines	227.56	6.31
AWE fixedwing1_fixed	282.00	8.80
AWE fixedwing2_fixed	370.00	12.20
AWE fixedwing1_float	312.00	9.96
AWE fixedwing2_float	400.00	13.36
Onshore wind turbines	99.50	2.58
AWE soft wing	164.88	1.59
PV_openfield	58.33	1.23
PV_rooftop	83.75	1.11

Figure A.1

A.2 System Costs

In Figure A.2, the system costs for all considered scenarios are presented.

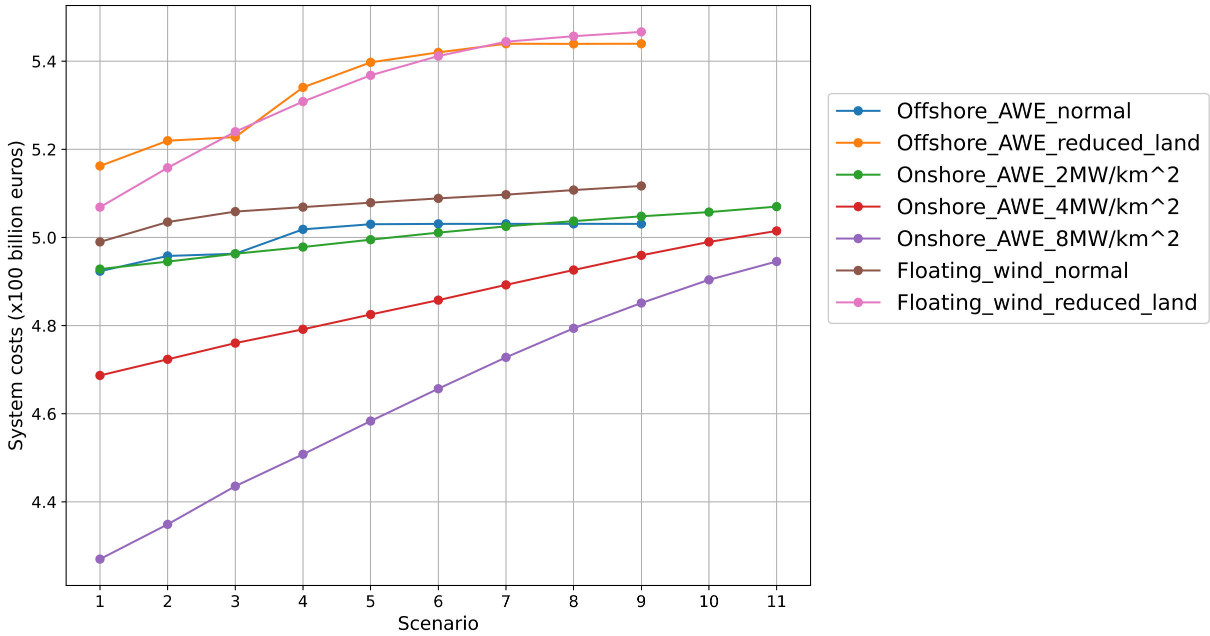


Figure A.2: System costs for all the evaluated scenarios. The numbers on the x-axis coincide with the scenarios that were defined in Section 6.3, with scenario 1 corresponding to the lowest cost assumption in that specific scenario.

A.3 All scenario outcomes

In this section, all scenario outcomes for total installed capacity are shown. The most important figure are displayed in Chapter 7.

A.3.1 Onshore AWE

In Figure A.3, Figure A.4 and Figure A.5, the outcomes for all onshore AWE scenarios are displayed. Apart from the scenarios from Section 6.3, the scenarios where the OPEX was matched to onshore wind turbines are also presented. This was done to isolate the cost trade-off between onshore AWE and onshore wind turbines

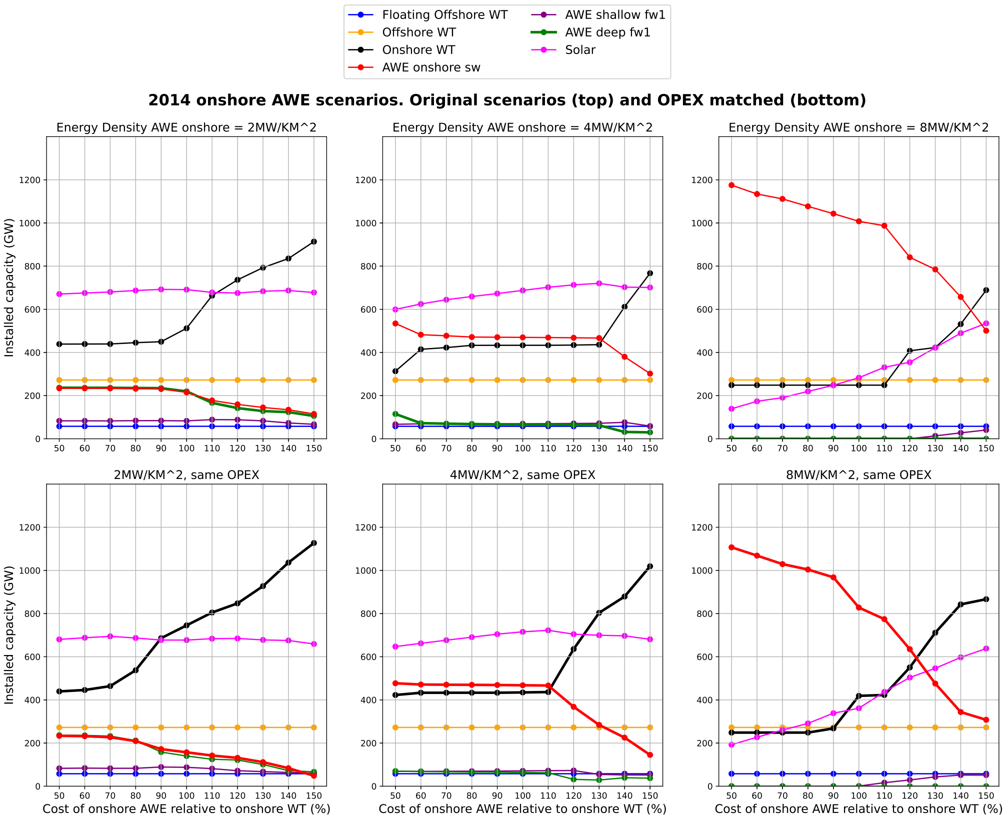


Figure A.3

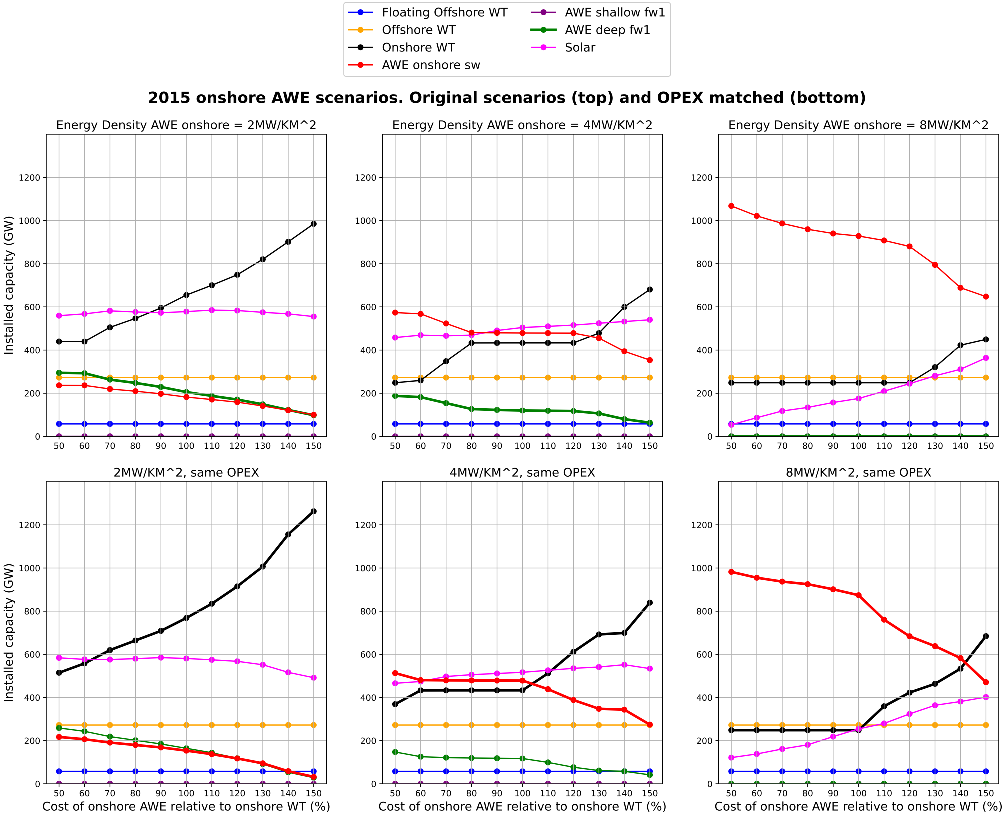


Figure A.4

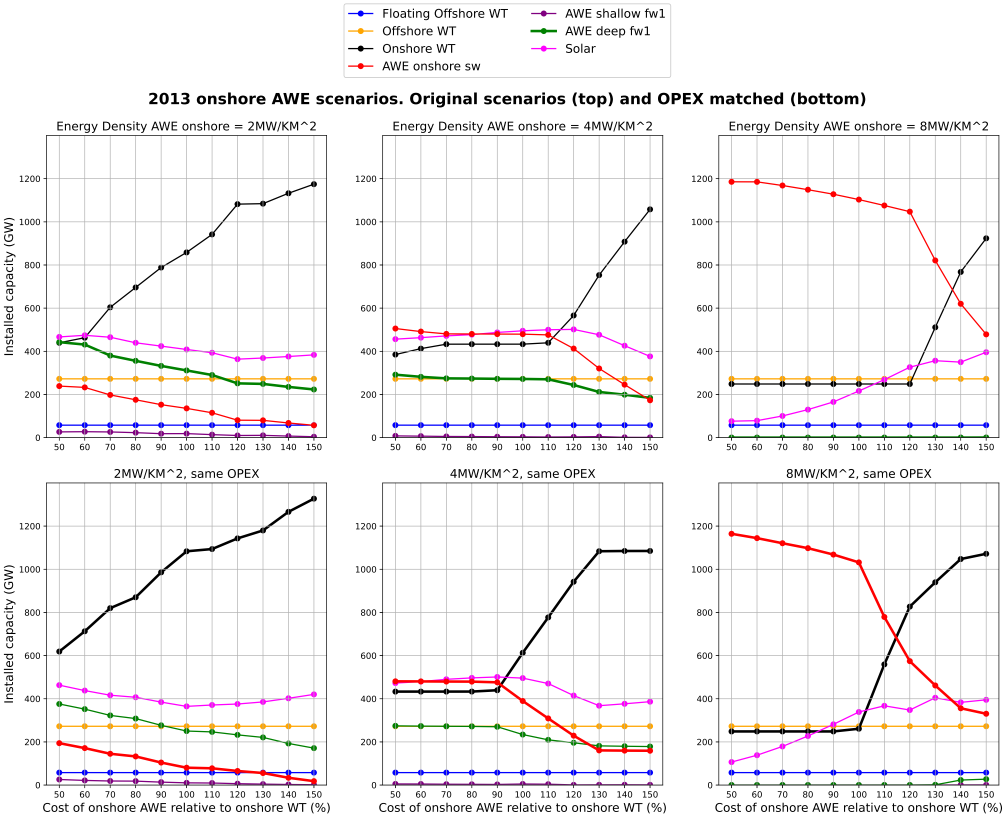


Figure A.5

A.3.2 Offshore AWE

In Figure A.6 all scenario outcomes for the offshore AWE scenarios are shown. The base case and the scenario with a more stringent land availability are displayed.

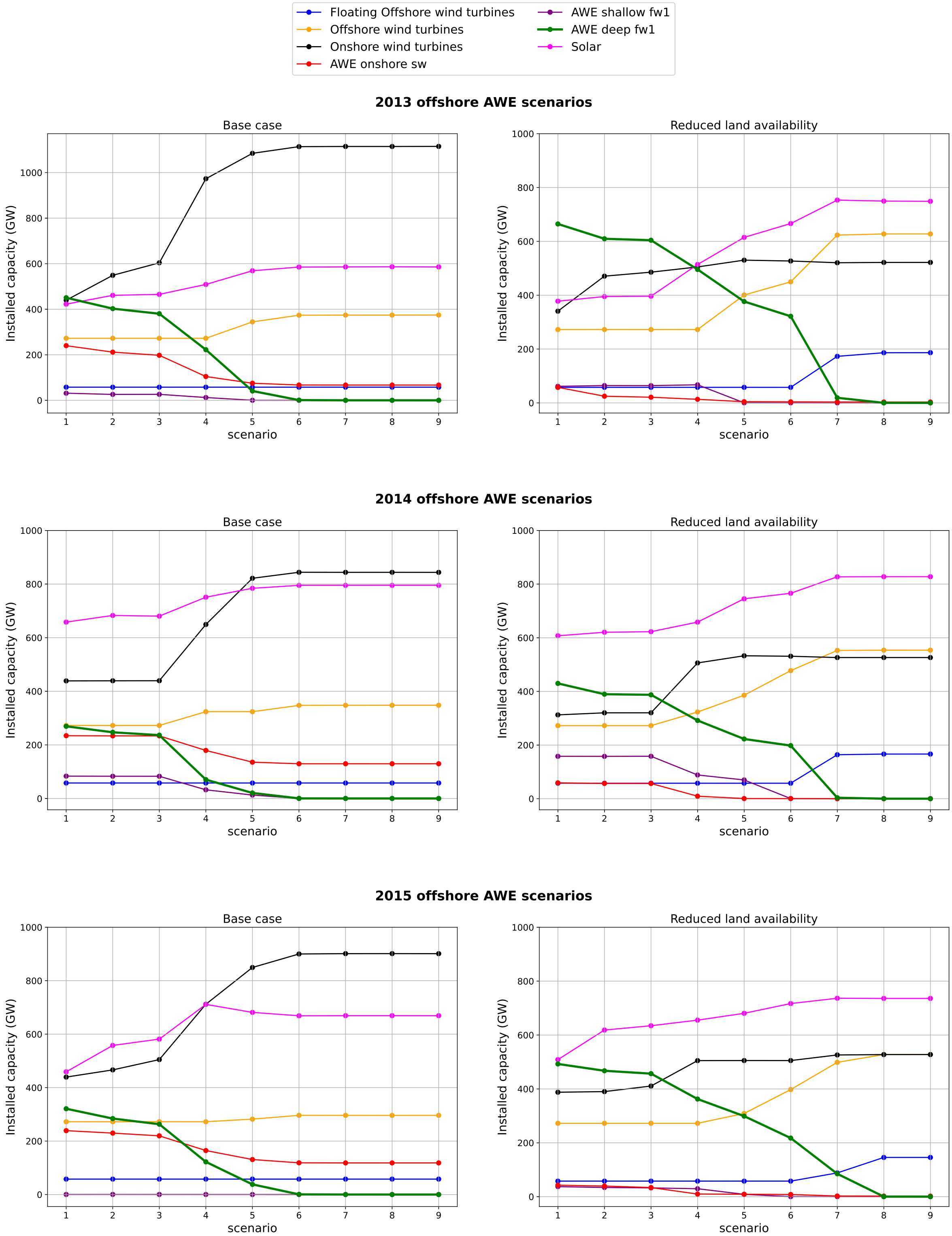


Figure A.6: Offshore AWE scenarios for all weather years, showing both the base case and the reduced land availability scenarios

A.3.3 Floating wind turbines

In Figure A.7 all scenario outcomes for the floating wind turbine scenarios are shown. The base case and the scenario with a more stringent land availability are displayed.

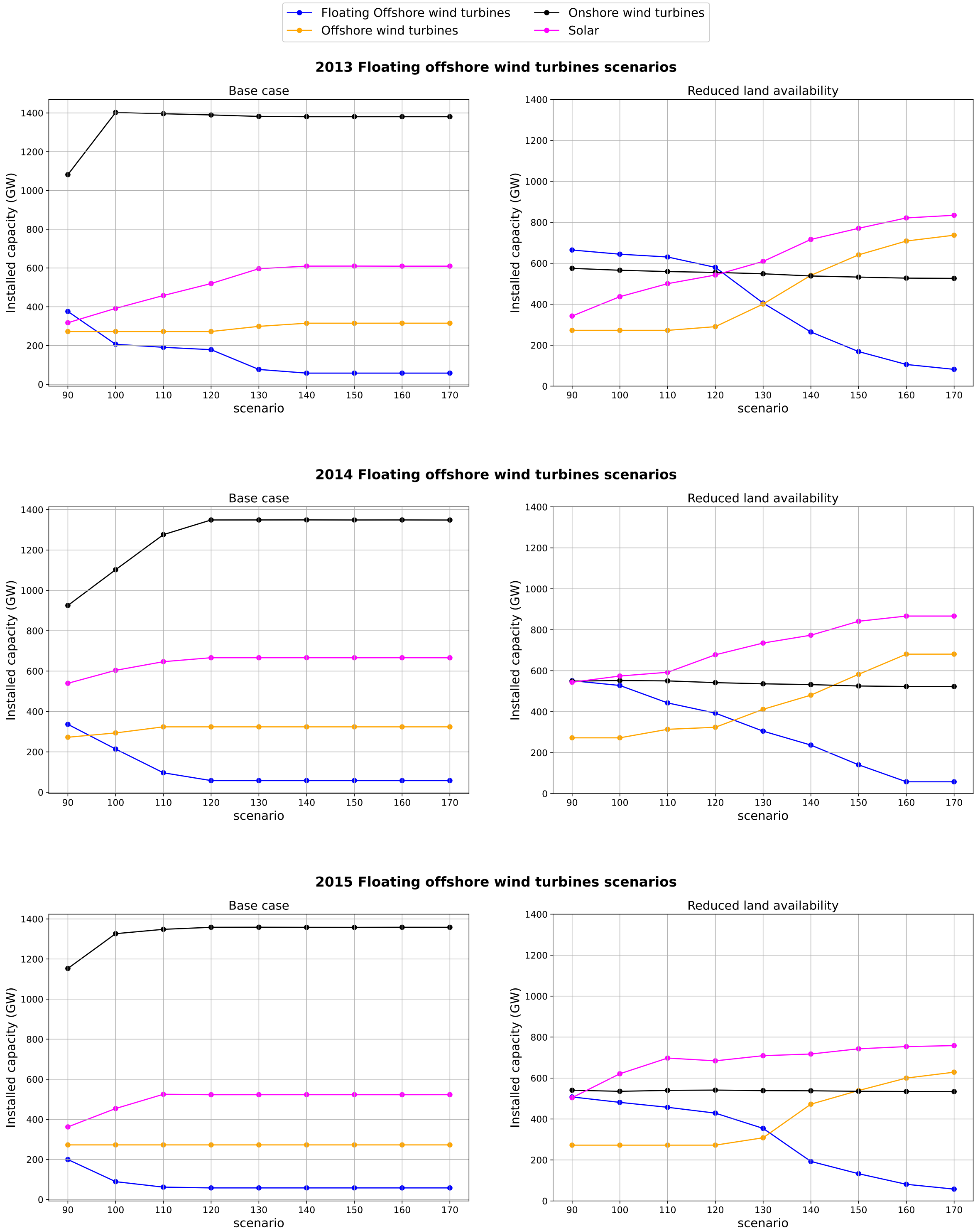


Figure A.7: Floating wind turbine scenarios for all weather years, showing both the base case and the reduced land availability scenarios

A.4 Geographical spreading

In this section, the installed capacity and generated energy per country are given for the most important supply technologies. This gives an idea of the distribution and concentration of the generation technologies.

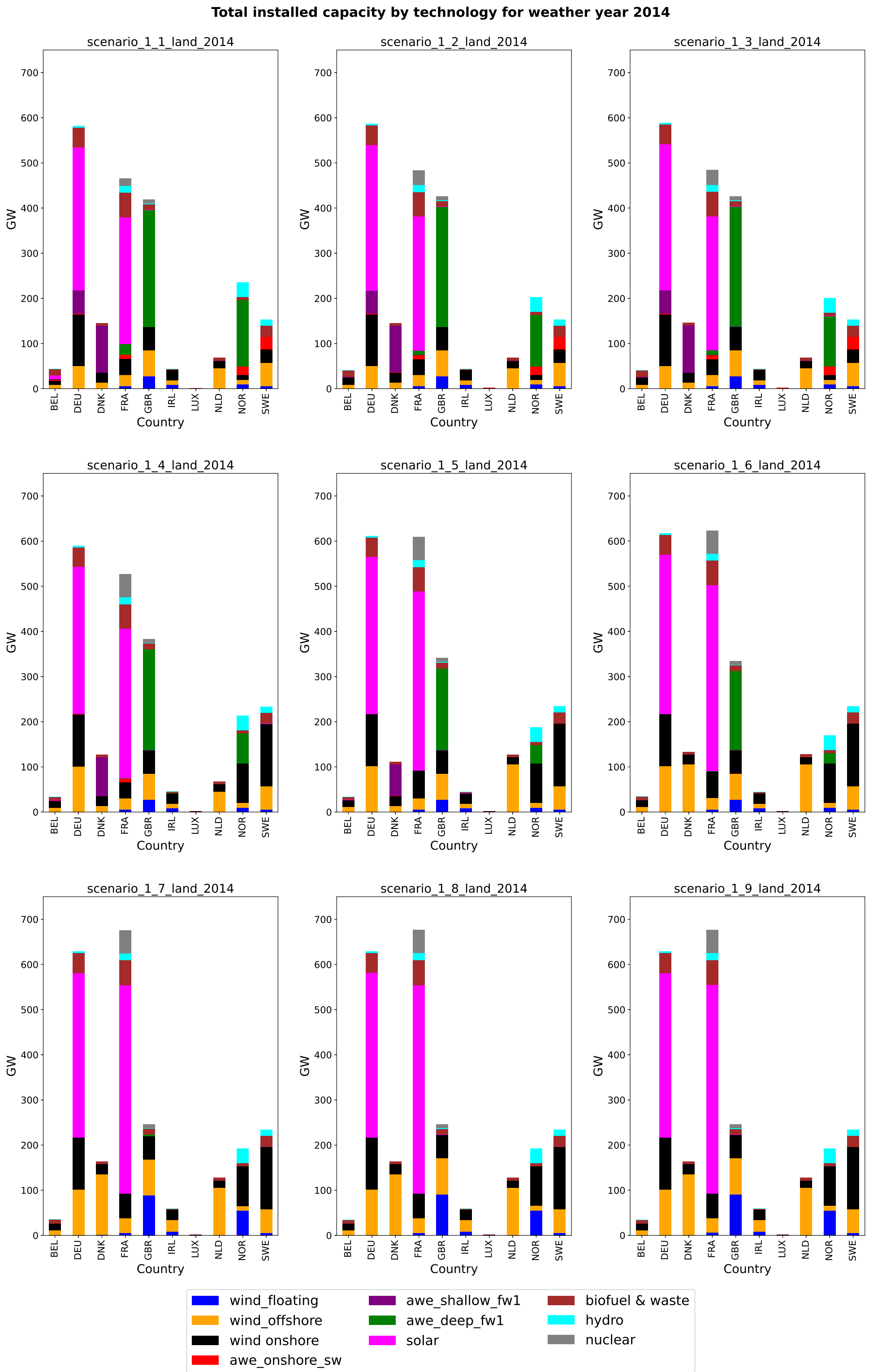


Figure A.8

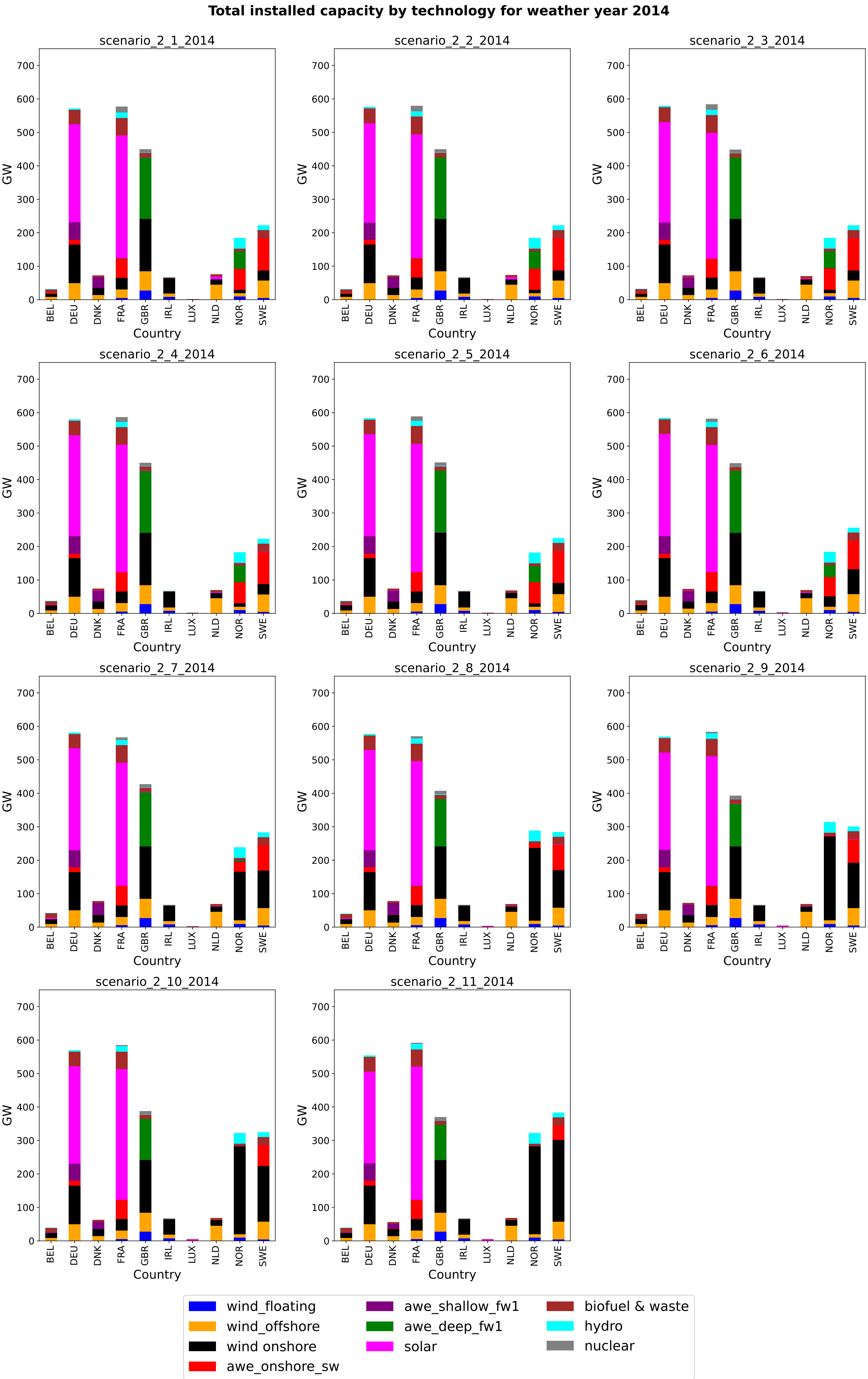

Total installed capacity by technology for weather year 2014
scenario_2_1_2014
scenario_2_2_2014
scenario_2_3_2014
scenario_2_4_2014
scenario_2_5_2014
scenario_2_6_2014
scenario_2_7_2014
scenario_2_8_2014
scenario_2_9_2014
scenario_2_10_2014
scenario_2_11_2014
GW
Country
BEL DEU DNK FRA GBR IRL LUX NLD NOR SWE
wind_floating
wind_offshore
wind onshore
awe_onshore_sw
awe_shallow_fw1
awe_deep_fw1
solar
biofuel & waste
hydro
nuclear

Figure A.9

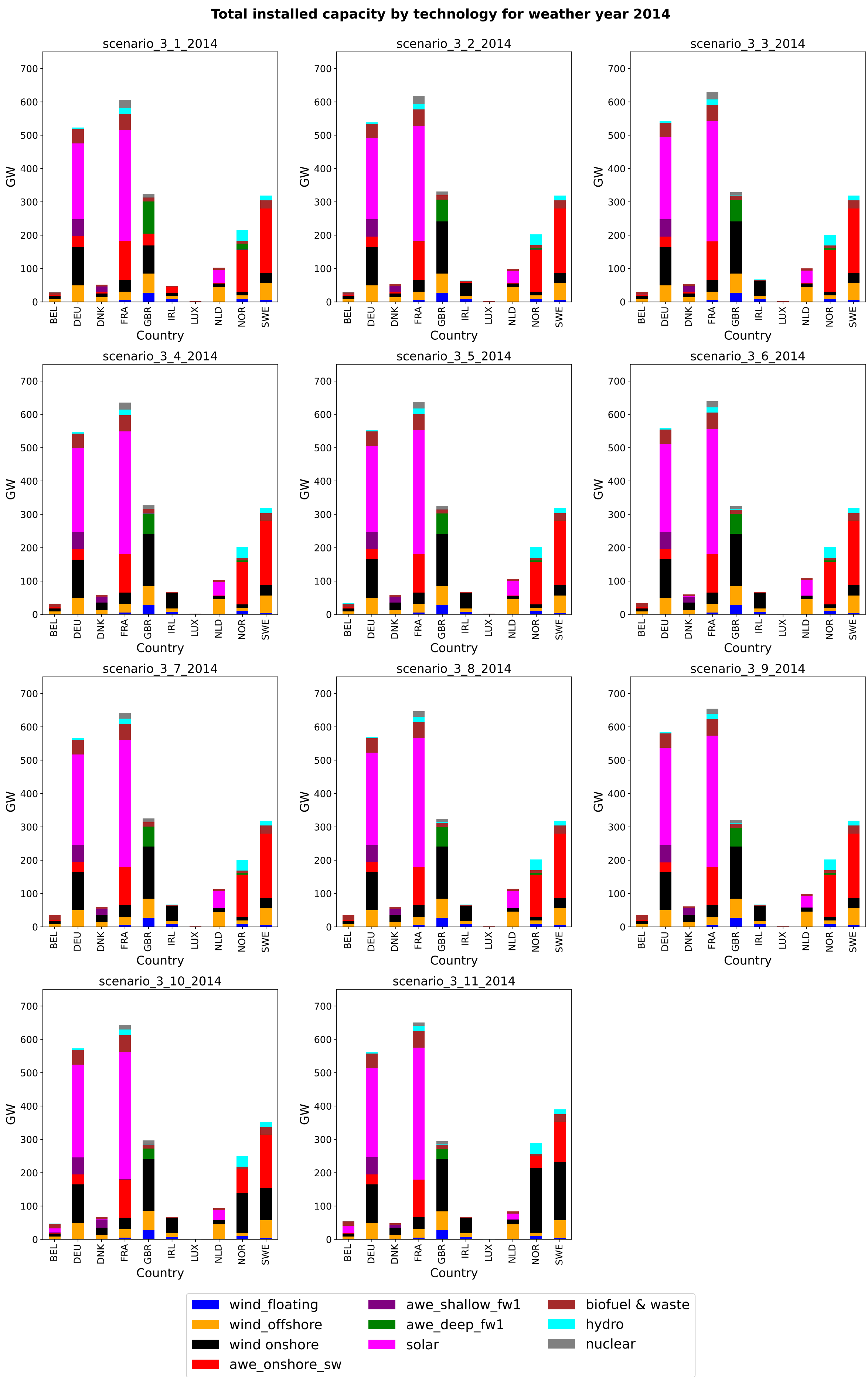

Total installed capacity by technology for weather year 2014
scenario_3_1_2014
scenario_3_2_2014
scenario_3_3_2014
scenario_3_4_2014
scenario_3_5_2014
scenario_3_6_2014
scenario_3_7_2014
scenario_3_8_2014
scenario_3_9_2014
scenario_3_10_2014
scenario_3_11_2014
GW
0
100
200
300
400
500
600
700
BEL
DEU
DNK
FRA
GBR
IRL
LUX
NLD
NOR
SWE
Country
wind_floating
wind_offshore
wind onshore
awe_onshore_sw
awe_shallow_fw1
awe_deep_fw1
solar
biofuel & waste
hydro
nuclear

Figure A.10

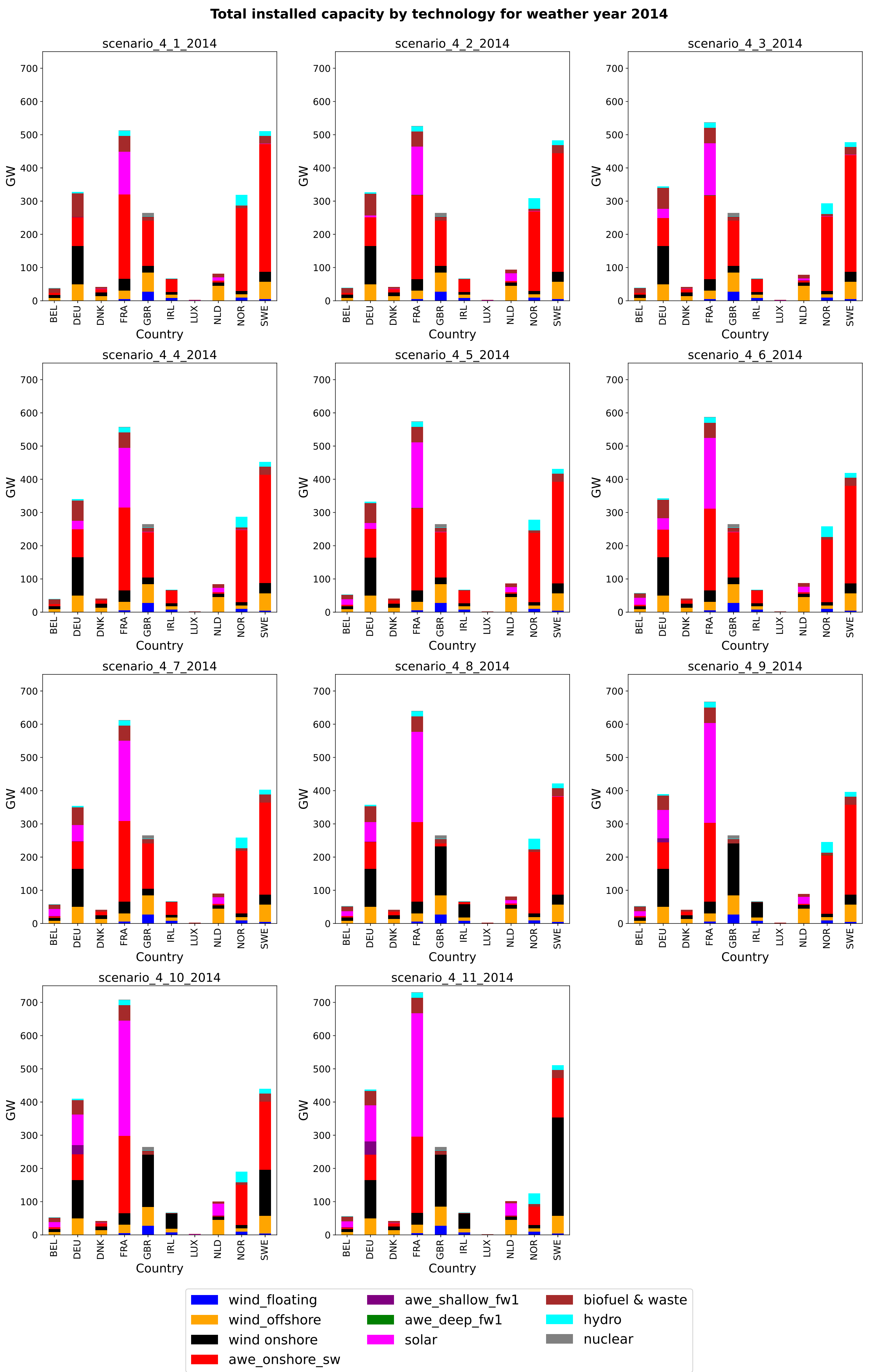

Total installed capacity by technology for weather year 2014
scenario_4_1_2014
scenario_4_2_2014
scenario_4_3_2014
scenario_4_4_2014
scenario_4_5_2014
scenario_4_6_2014
scenario_4_7_2014
scenario_4_8_2014
scenario_4_9_2014
scenario_4_10_2014
scenario_4_11_2014
GW
Country
BEL DEU DNK FRA GBR IRL LUX NLD NOR SWE
0 100 200 300 400 500 600 700
wind_floating
wind_offshore
wind onshore
awe_onshore_sw
awe_shallow_fw1
awe_deep_fw1
solar
biofuel & waste
hydro
nuclear

Figure A.11

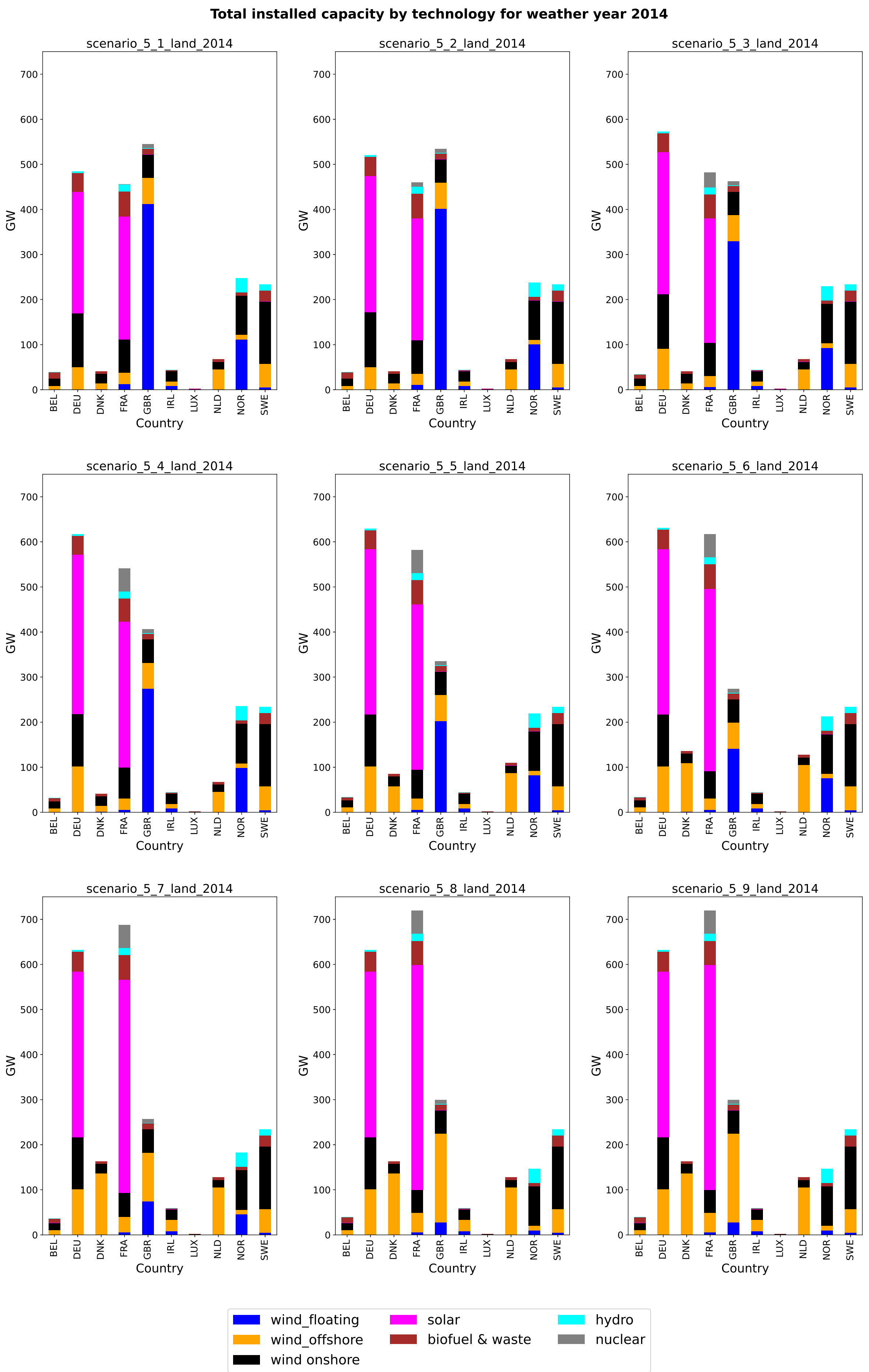

Total installed capacity by technology for weather year 2014
scenario_5_1_land_2014
scenario_5_2_land_2014
scenario_5_3_land_2014
scenario_5_4_land_2014
scenario_5_5_land_2014
scenario_5_6_land_2014
scenario_5_7_land_2014
scenario_5_8_land_2014
scenario_5_9_land_2014
GW
Country
BEL DEU DNK FRA GBR IRL LUX NLD NOR SWE
0 100 200 300 400 500 600 700
wind_floating
wind_offshore
wind onshore
solar
biofuel & waste
hydro
nuclear

Figure A.12

Appendix B

Spatial potential

In this appendix chapter, the coordinates for the representative points method and the World Bank (2019) study for offshore wind potentials are given.

B.1 Coordinates

This section gives the coordinates of all the representative points for onshore AWE, shallow water AWE, deep water AWE, fixed-bottom offshore wind turbines, and floating wind turbines.

Country	Location	West_longitude	East_longitude	North_latitude	South_latitude
Norway	NOR1onshore	7.5	7.75	60.25	60
Norway	NOR2onshore	10.25	10.5	62.75	62.5
Norway	NOR3onshore	14.25	14.5	65.5	65.25
Norway	NOR4onshore	25.75	26	70.25	70
Norway	NOR5onshore	22.5	22.75	69.75	69.5
Sweden	SWE1onshore	13	13.25	58.25	58
Sweden	SWE2onshore	15.5	15.75	58.5	58.25
Sweden	SWE3onshore	19.5	19.75	64.5	64.25
Sweden	SWE4onshore	13.25	13.5	63.25	63
Sweden	SWE5onshore	16.25	16.5	60.5	60.25
Denmark	DEN1onshore	9	9.25	55.25	55
Denmark	DEN2onshore	8.5	8.75	56.25	56
Denmark	DEN3onshore	10.5	10.75	56.5	56.25
Denmark	DEN4onshore	11.25	11.5	55	54.75
Denmark	DEN5onshore	10.5	10.75	55.25	55
Germany	GER1onshore	12.75	13	53.5	53.25
Germany	GER2onshore	11	11.25	52.25	52
Germany	GER3onshore	8	8.25	53	52.75
Germany	GER4onshore	10.5	10.75	51.5	51.25
Germany	GER5onshore	9.25	9.5	54.5	54.25
Netherlands	NED1onshore	3.75	4	51.75	51.5
Netherlands	NED2onshore	4.75	5	52.25	52
Netherlands	NED3onshore	5.5	5.75	53.25	53
Netherlands	NED4onshore	5.75	6	52.75	52.5
Netherlands	NED5onshore	6.75	7	53.25	53
Belgium	BEL1onshore	2.75	3	50.75	51
Belgium	BEL2onshore	3.5	3.75	50.75	50.5
Belgium	BEL3onshore	4.75	5	50.75	50.5
Belgium	BEL4onshore	4.25	4.5	50.25	50
Belgium	BEL5onshore	4	4.25	51.25	51
Luxembourg	LUX1onshore	6	6.25	49.75	49.5
France	FRA1onshore	2	2.25	50.5	50.25
France	FRA2onshore	-1.25	-1	49	48.75
France	FRA3onshore	2.75	3	43.25	43
France	FRA4onshore	4.5	4.75	43.75	43.5
France	FRA5onshore	-3.5	-3.25	48.5	48.25
France	FRA6onshore	-0.5	-0.25	46.75	46.5
UK	UK1onshore	-4	-3.75	51	50.75
UK	UK2onshore	-1.75	-1.5	51.5	51.25
UK	UK3onshore	0.25	0.5	52.5	52.25
UK	UK4onshore	-4	-3.75	52.25	52
UK	UK5onshore	-0.5	-0.25	53.25	53
UK	UK6onshore	-2.75	-2.5	55.75	55.5
UK	UK7onshore	-3	-2.75	57.5	57.25
Ireland	IRE1onshore	-9	-8.75	52	51.75
Ireland	IRE2onshore	-8	-7.75	54.5	54.25
Ireland	IRE3onshore	-7.5	-7.25	53.25	53
Ireland	IRE4onshore	-7.5	-7.25	52.5	52.25
Ireland	IRE5onshore	-6.75	-6.5	53	52.75

Figure B.1: Coordinates that were used for representative points for onshore AWE

Country	Location	West_longitude	East_longitude	North_latitude	South_latitude
Norway	NOR6fixed	5.25	5.5	59	58.75
Norway	NOR7fixed	11.75	12	65.5	65.25
Norway	NOR8fixed	16.25	16.5	69.5	69.25
Norway	NOR9fixed	20.5	20.75	70.5	70.25
Sweden	SWE6fixed	22.25	22.5	65.5	65.25
Sweden	SWE7fixed	20.25	20.5	63.5	63.25
Sweden	SWE8fixed	12.25	12.5	56.75	56.5
Sweden	SWE9fixed	17.25	17.5	56	55.75
Sweden	SWE10fixed	13.25	13.5	55.25	55
Denmark	DEN6fixed	7.25	7.5	56.75	56.5
Denmark	DEN7fixed	7.25	7.5	55.75	55.5
Denmark	DEN8fixed	11.25	11.5	56.5	56.25
Denmark	DEN9fixed	12.25	12.5	54.75	54.5
Germany	GER6fixed	7.25	7.5	55	54.75
Germany	GER7fixed	6.75	7	54	53.75
Germany	GER8fixed	11.5	11.75	54.5	54.25
Germany	GER9fixed	14	14.25	55	54.75
Netherlands	NED6fixed	3.25	3.5	52	51.75
Netherlands	NED7fixed	3.75	4	53	52.75
Netherlands	NED8fixed	4	4.25	54.5	54.25
Netherlands	NED9fixed	5.75	6	54	53.75
Belgium	BEL4fixed	2.5	2.75	51.75	51.5
Belgium	BEL5fixed	2.75	3	51.5	51.25
France	FRA6fixed	0.5	0.75	50.25	50
France	FRA7fixed	-2.5	-2.25	49	48.75
France	FRA8fixed	-2.75	-2.5	47.25	47
France	FRA9fixed	-2	-1.75	46	45.75
France	FRA10fixed	4	4.25	43.5	43.25
UK	UK6fixed	-4	-3.75	53.75	53.5
UK	UK7fixed	-4.75	-4.5	51.5	51.25
UK	UK8fixed	1.75	2	52	51.75
UK	UK9fixed	1.5	1.75	53.75	53.5
UK	UK10fixed	-3.25	-3	58	57.75
Ireland	IRE6fixed	-9	-8.75	54.5	54.25
Ireland	IRE7fixed	-7.5	-7.25	55.75	55.5
Ireland	IRE8fixed	-7.5	-7.25	52	51.75
Ireland	IRE9fixed	-6	-5.75	54	53.75

Figure B.2: Coordinates that were used for representative points for fixed-bottom offshore wind turbines and shallow water AWE

Country	Location	West_longitude	East_longitude	North_latitude	South_latitude
Norway	NOR6float	5.25	5.5	58.25	58
Norway	NOR7float	3.25	3.5	62.25	62
Norway	NOR8float	9.75	10	67	66.75
Norway	NOR9float	26	26.25	72.5	72.25
Norway	NOR10float	17	17.25	71.5	71.25
Sweden	SWE6float	10.5	10.75	58.5	58.25
Sweden	SWE7float	18	18.25	58.25	58
Sweden	SWE8float	19	19.25	62.5	62.25
Sweden	SWE9float	22.5	22.75	65	64.75
Sweden	SWE10float	19.75	20	59	58.75
Sweden	SWE11float	19	19.25	56.5	56.25
Sweden	SWE12float	15.75	16	55.5	55.25
Denmark	DEN6float	15.5	15.75	55.5	55.25
Denmark	DEN7float	10	10.25	58.25	58
Denmark	DEN8float	5.5	5.75	56.5	56.25
France	FRA6float	-1.5	-1.25	50	49.75
France	FRA7float	-5	-4.75	49	48.75
France	FRA8float	-4.75	-4.5	47.25	47
France	FRA9float	-3.5	-3.25	46	45.75
France	FRA10float	4.5	4.75	43	42.75
UK	UK6float	-6	-5.75	49.5	49.25
UK	UK7float	0.5	0.75	55.25	55
UK	UK8float	-1	-0.75	58.75	58.5
UK	UK9float	-4	-3.75	59	58.75
UK	UK10float	-8.5	-8.25	58.75	58.5
Ireland	IRE6float	-9.5	-9.25	55	54.75
Ireland	IRE7float	-11.25	-11	53	52.75
Ireland	IRE8float	-10.5	-10.25	51	50.75
Ireland	IRE9float	-7.25	-7	51.75	51.5

Figure B.3: Coordinates that were used for representative points for floating wind turbines and deep water AWE

B.2 Potential area

In this section, the offshore wind potential maps from World Bank (2019) are presented. These maps were used for determining representative points and computing the maximal installed capacity constraints for both conventional offshore wind and floating wind turbines.

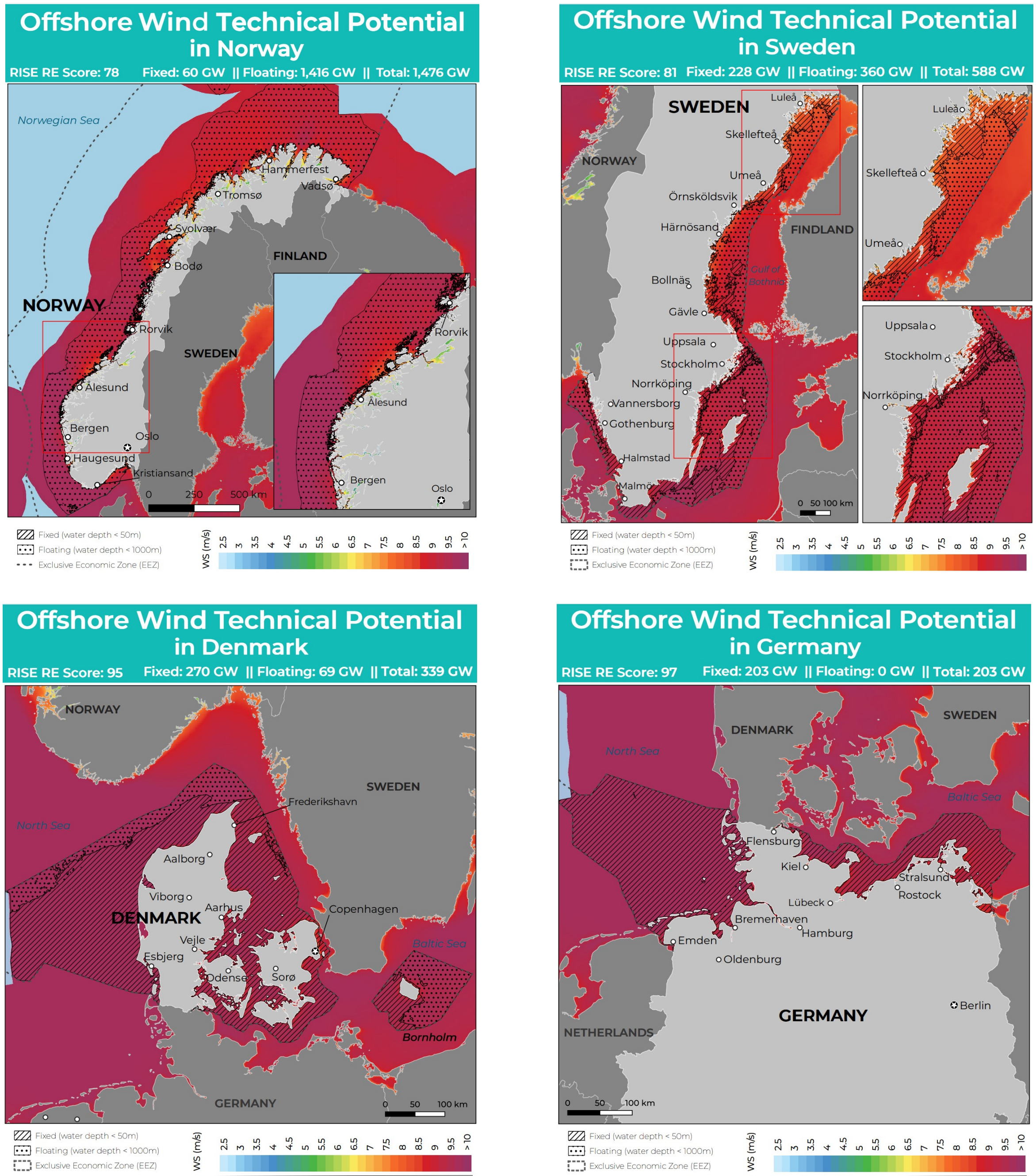
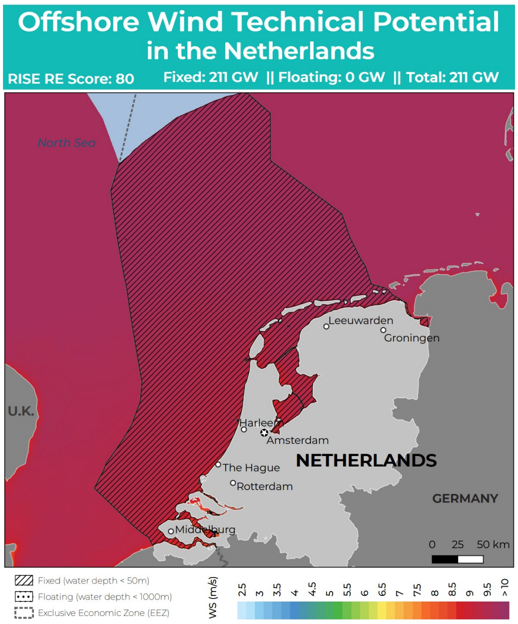
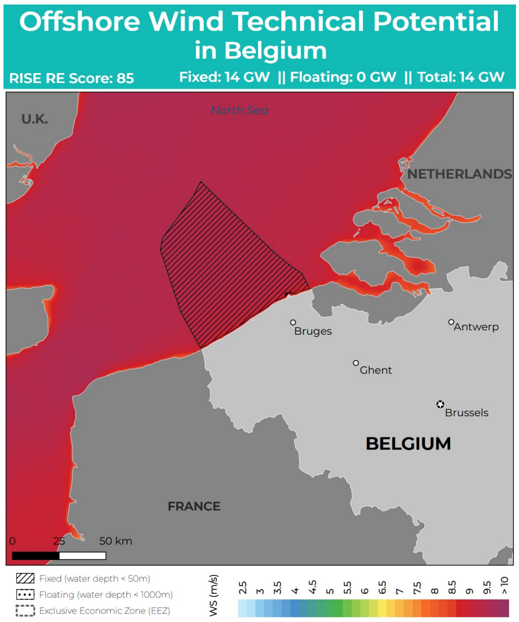
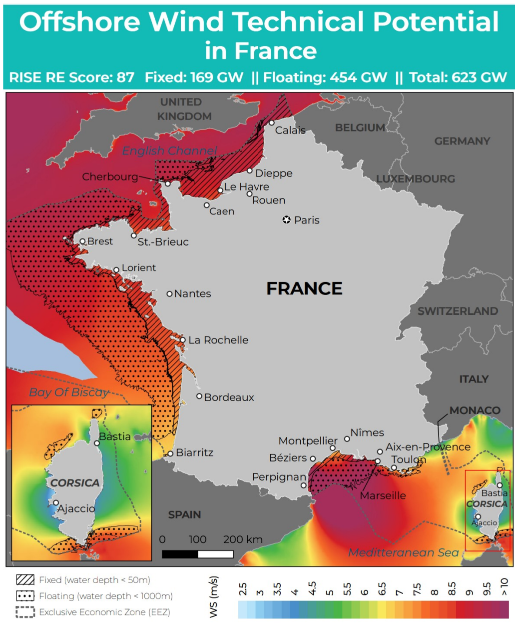
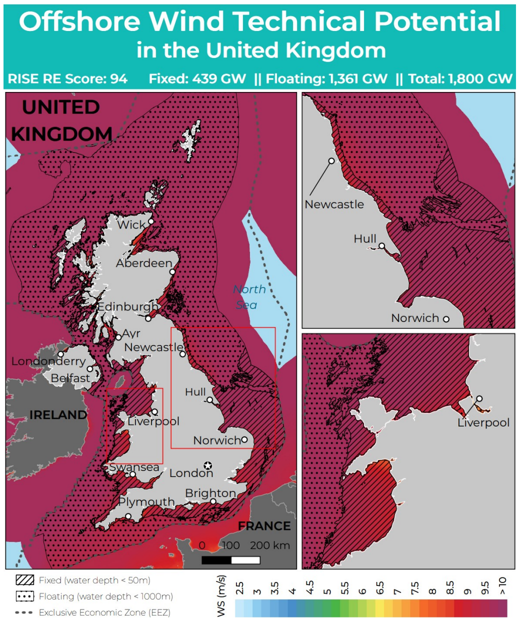


Figure B.4: Country specific offshore wind technical potentials, according to World Bank (2019)









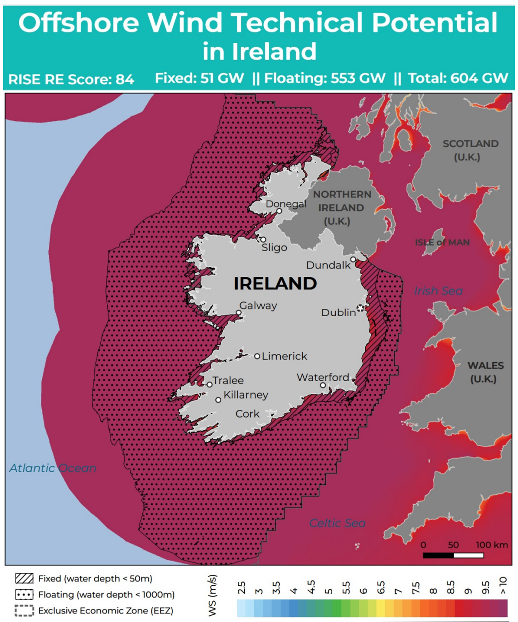


Figure B.5: Country specific offshore wind technical potentials, according to World Bank (2019)

Appendix C

Load duration curves

In this appendix chapter, the load duration curves for different rivaling wind technologies are presented relative to each other. This is done for each country individually.

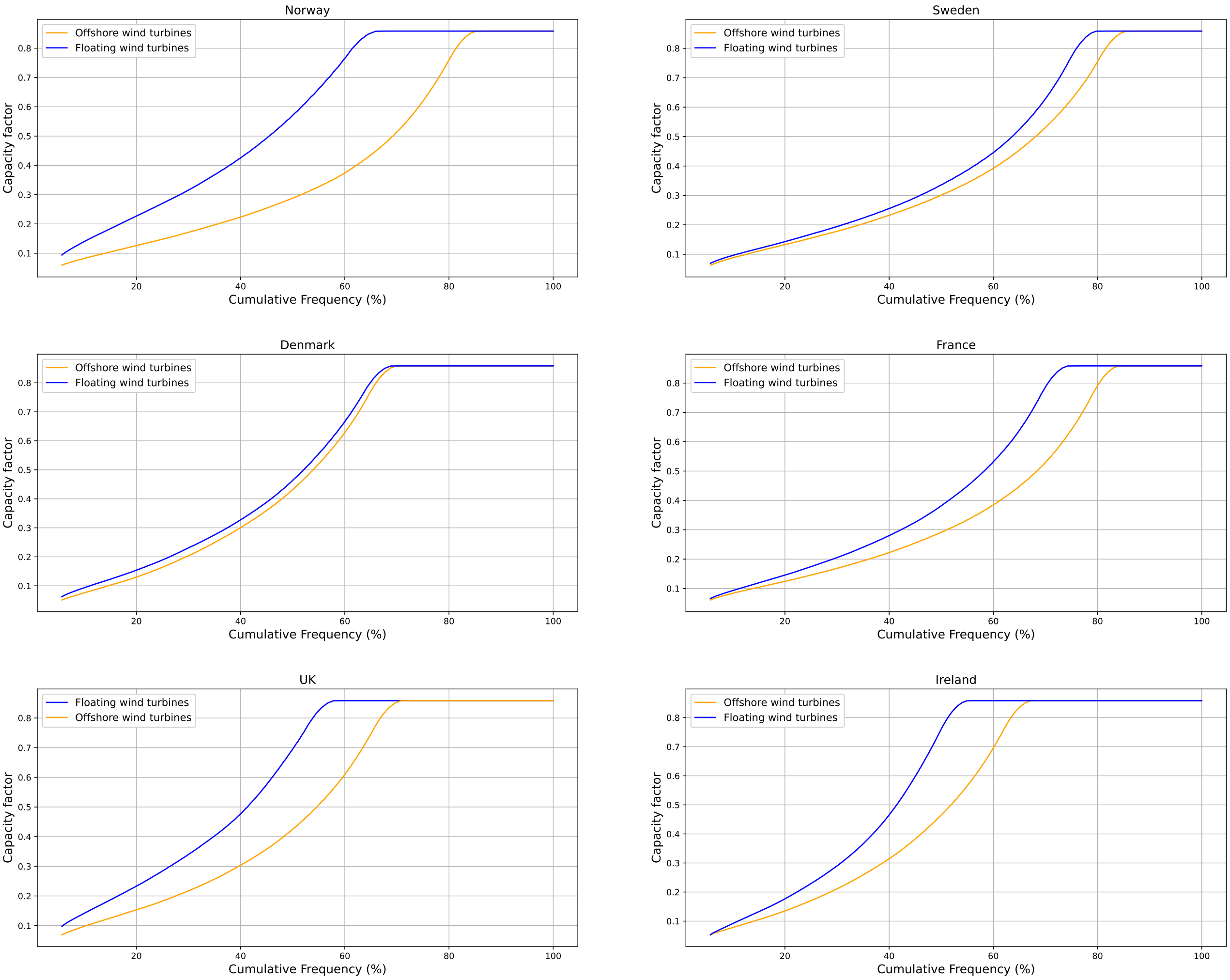


Figure C.1: Load duration curves for floating wind turbines vs. conventional offshore wind turbines.

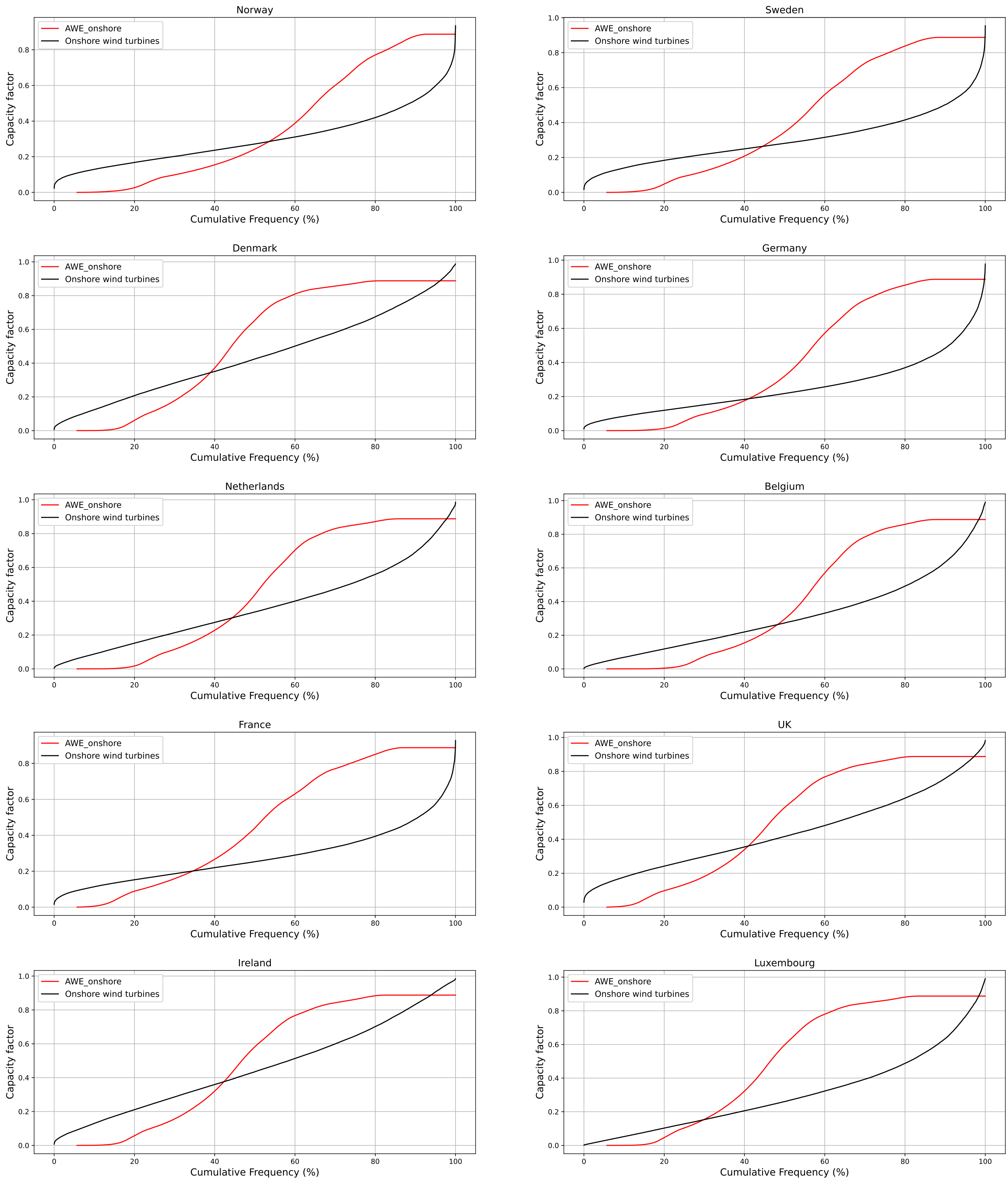


Figure C.2: Load duration curves for onshore AWE vs. onshore wind turbines.

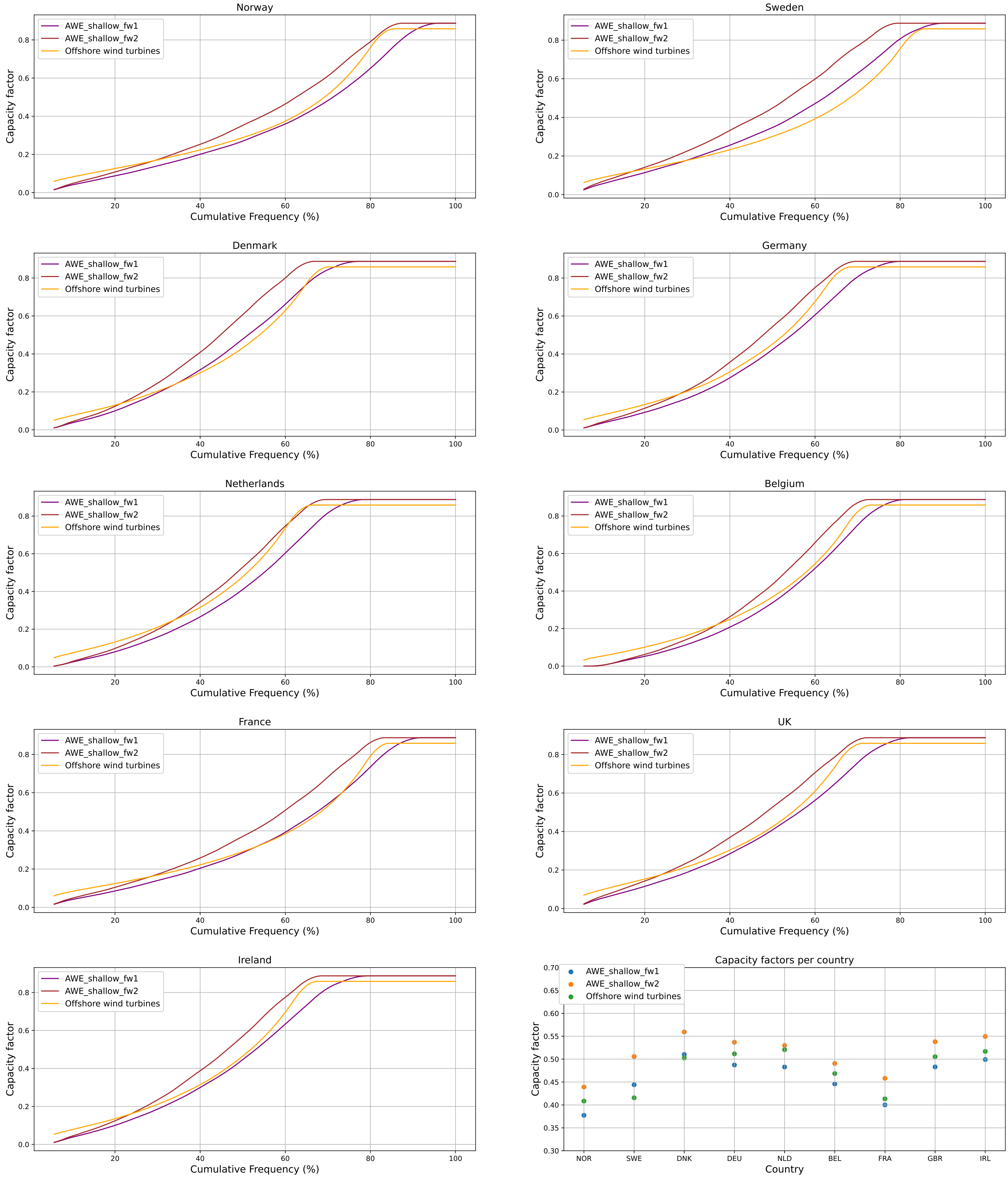


Figure C.3: Load duration curves for shallow water AWE vs. fixed-bottom offshore wind turbines

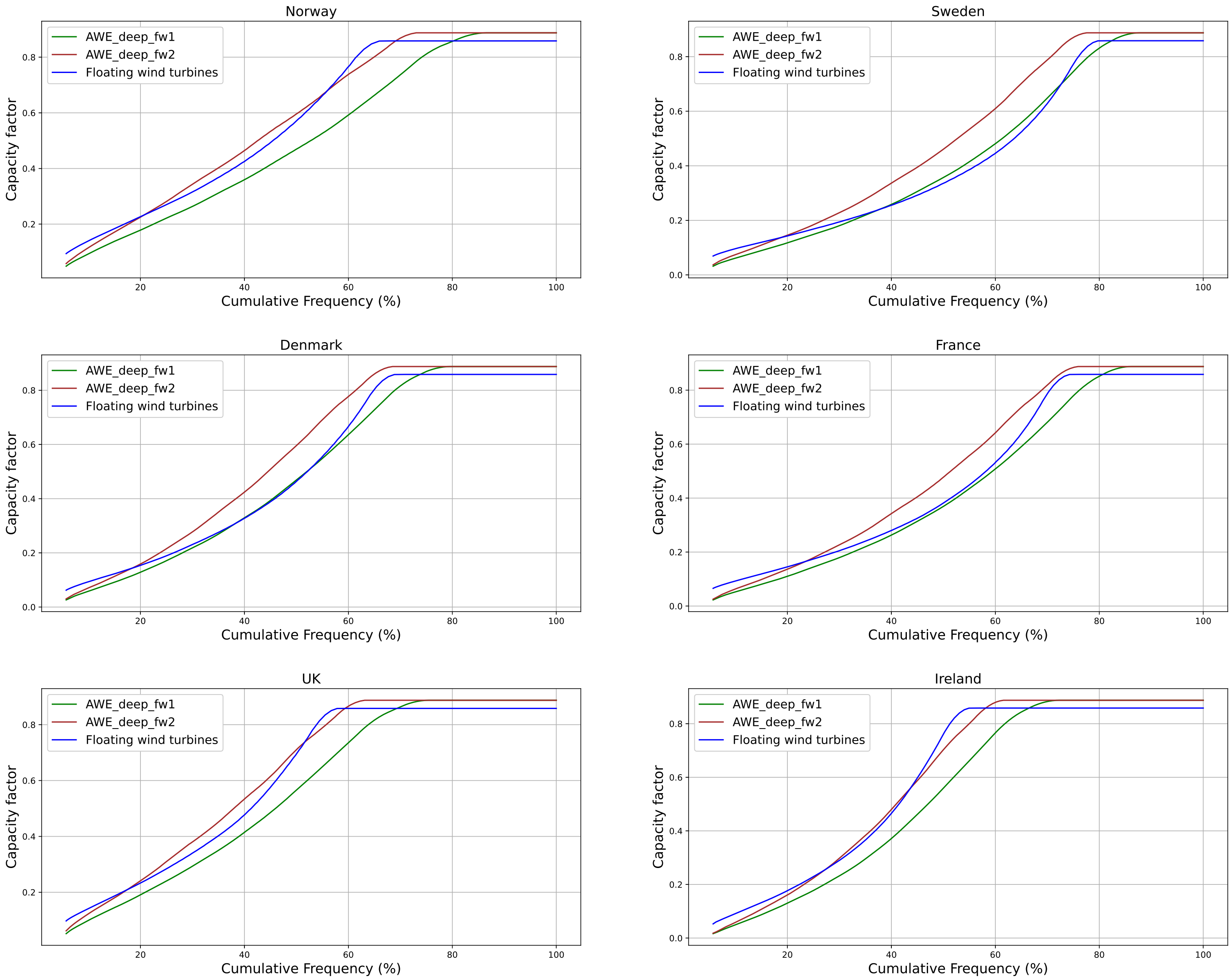


Figure C.4: Load duration curves for floating wind turbines vs. deep water AWE

Appendix D

Settings

D.1 Settings

In this section, the relevant model settings that were used in this study are presented.

D.1.1 Land availability

In Figure D.1 and Figure D.2 the land availability constraints are given for the base case and the reduced land availability scenario respectively. The available surface can be utilized by onshore wind turbines, onshore AWE, and solar energy. In Figure D.1 the maximal amount of solar energy that remained from taking 13.5% of the Eurocalliope model is also presented.

Country	Available area (km^2)	PV max (GW)
NOR	32930	1105
SWE	51916	947
DNK	2748	164
DEU	25295	1099
NLD	2048	114
BEL	1958	81
FRA	37830	2034
GBR	19560	828
IRL	5726	307
LUX	199	7

Figure D.1: Base case land availability constraints and corresponding maximal solar energy (PV) capacity

Country	Available area (km^2)
NOR	10977
SWE	17305
DNK	2748
DEU	18971
NLD	2048
BEL	1958
FRA	12610
GBR	6520
IRL	2863
LUX	199

Figure D.2: The reduced land availability constraints, used for offshore AWE and floating wind turbine scenarios

D.1.2 Minimal installed capacities

In Figure D.3 the minimal installed capacities used as constraints in the model runs are given. The average of countries' 2030 and 2050 policy targets was taken as a guideline. In some cases, the inputs were adjusted to align with industry expectations when official guidelines were lacking. When 2050 policy goals were lacking, the 2030 goals were usually taken as inputs.

Country	Onshore Wind, policy targets (GW),			
	2030	2050	Average	Inputs
NOR	10	-	10	10
SWE	30	-	30	30
DNK	11.5	-	11.5	11.5
DEU	115	-	115	115
NLD	9	-	9	9
BEL	9	-	9	9
FRA	35	60	47.5	35
GBR	20	-	20	20
IRL	8	-	8	8
LUX	1	-	1	1
Total	**248.5**	**60**	**261**	**248.5**

Country	Offshore Wind, policy targets (GW)			
	2030	2050	Average	Inputs
NOR	5	-	5	10
SWE	15	90	52.5	52.5
DNK	12.9	-	12.9	12.9
DEU	30	70	50	50
NLD	21	70	45.5	45.5
BEL	8	10	9	9
FRA	10	40	25	25
GBR	45	70	57.5	57.5
IRL	5	15	10	10
LUX	-	-	-	0
Total:	**151.9**	**365**	**267.4**	**272.4**

Country	Floating Wind, policy targets,			
	2030	2050	Average	Inputs
NOR	3	-	3	10
SWE	-	-	-	5
DNK	-	-	-	10
FRA	1.5	10	5.75	5.75
GBR	5	50	27.5	27.5
IRL	2	15	8.5	8.5
Total	**11.5**	**75**	**44.75**	**66.75**

Figure D.3: Minimal installed capacity inputs for the model, based on policy targets of North Sea countries.

D.1.3 Maximal technical potential

Figure D.4 gives the offshore wind potentials that were derived from the ESMAP study (World Bank, 2019), taking a maximal energy density of 2MW/km^2 in line with the physical limit that was discussed in Section 4.3.

Floating wind

Country	MW potential (ESMAP) (4MW/km2)	km^2	GW Potential (2 MW/km2)
NOR	1416	354000	708
SWE	360	90000	180
DNK	69	17250	34.5
FRA	454	113500	227
UK	1361	340250	680.5
IRL	553	138250	276.5

Offshore wind

Country	MW potential (ESMAP) (4MW/km2)	km^2	GW Potential (2 MW/km2)
NOR	60	15000	30
SWE	228	57000	114
DNK	270	67500	135
DEU	203	50750	101.5
NLD	211	52750	105.5
BEL	14	3500	7
FRA	169	42250	84.5
UK	439	109750	219.5
IRL	51	12750	25.5

Figure D.4: The computation of the maximal technical potential for floating and conventional offshore wind. the constraints were used for floating wind turbines and deep water AWE combined and for conventional offshore wind and shallow water AWE combined.

Appendix E

Correlation

In Figure E.1 and Figure E.2, the Pearson correlations between different offshore wind technologies are given for the weather year 2014.

NORWAY

	Wind_onshore_NOR	AWE_onshore_NOR	Wind_offshore_NOR	AWE_shallow_NOR	AWE_deep_NOR	Wind_floating_NOR
Wind_onshore_NOR	1.00	0.89	0.79	0.75	0.74	0.64
AWE_onshore_NOR	0.89	1.00	0.72	0.71	0.70	0.59
Wind_offshore_NOR	0.79	0.72	1.00	0.93	0.82	0.68
AWE_shallow_NOR	0.75	0.71	0.93	1.00	0.81	0.65
AWE_deep_NOR	0.74	0.70	0.82	0.81	1.00	0.83
Wind_floating_NOR	0.64	0.59	0.68	0.65	0.83	1.00

SWEDEN

	Wind_onshore_SWE	AWE_onshore_SWE	Wind_offshore_SWE	AWE_shallow_SWE	AWE_deep_SWE	Wind_floating_SWE
Wind_onshore_SWE	1.00	0.75	0.71	0.69	0.73	0.73
AWE_onshore_SWE	0.75	1.00	0.69	0.71	0.79	0.78
Wind_offshore_SWE	0.71	0.69	1.00	0.95	0.84	0.88
AWE_shallow_SWE	0.69	0.71	0.95	1.00	0.86	0.85
AWE_deep_SWE	0.73	0.79	0.84	0.86	1.00	0.96
Wind_floating_SWE	0.73	0.78	0.88	0.85	0.96	1.00

DENMARK

	Wind_onshore_DNK	AWE_onshore_DNK	Wind_offshore_DNK	AWE_shallow_DNK	AWE_deep_DNK	Wind_floating_DNK
Wind_onshore_DNK	1.00	0.86	0.91	0.91	0.83	0.83
AWE_onshore_DNK	0.86	1.00	0.88	0.93	0.75	0.76
Wind_offshore_DNK	0.91	0.88	1.00	0.96	0.85	0.88
AWE_shallow_DNK	0.91	0.93	0.96	1.00	0.86	0.86
AWE_deep_DNK	0.83	0.75	0.85	0.86	1.00	0.96
Wind_floating_DNK	0.83	0.76	0.88	0.86	0.96	1.00

FRANCE

	Wind_onshore_FRA	AWE_onshore_FRA	Wind_offshore_FRA	AWE_shallow_FRA	AWE_deep_FRA	Wind_floating_FRA
Wind_onshore_FRA	1.00	0.76	0.80	0.81	0.72	0.69
AWE_onshore_FRA	0.76	1.00	0.84	0.87	0.83	0.80
Wind_offshore_FRA	0.80	0.84	1.00	0.95	0.89	0.89
AWE_shallow_FRA	0.81	0.87	0.95	1.00	0.90	0.86
AWE_deep_FRA	0.72	0.83	0.89	0.90	1.00	0.96
Wind_floating_FRA	0.69	0.80	0.89	0.86	0.96	1.00

GREAT BRITAIN

	Wind_onshore_GBR	AWE_onshore_GBR	Wind_offshore_GBR	AWE_shallow_GBR	AWE_deep_GBR	Wind_floating_GBR
Wind_onshore_GBR	1.00	0.85	0.89	0.90	0.75	0.71
AWE_onshore_GBR	0.85	1.00	0.92	0.93	0.68	0.67
Wind_offshore_GBR	0.89	0.92	1.00	0.97	0.73	0.71
AWE_shallow_GBR	0.90	0.93	0.97	1.00	0.73	0.70
AWE_deep_GBR	0.75	0.68	0.73	0.73	1.00	0.95
Wind_floating_GBR	0.71	0.67	0.71	0.70	0.95	1.00

IRELAND

	Wind_onshore_IRL	AWE_onshore_IRL	Wind_offshore_IRL	AWE_shallow_IRL	AWE_deep_IRL	Wind_floating_IRL
Wind_onshore_IRL	1.00	0.87	0.89	0.87	0.88	0.79
AWE_onshore_IRL	0.87	1.00	0.90	0.88	0.88	0.77
Wind_offshore_IRL	0.89	0.90	1.00	0.95	0.86	0.79
AWE_shallow_IRL	0.87	0.88	0.95	1.00	0.83	0.73
AWE_deep_IRL	0.88	0.88	0.86	0.83	1.00	0.91
Wind_floating_IRL	0.79	0.77	0.79	0.73	0.91	1.00

Figure E.1: Correlations between offshore wind technologies for countries where there is potential for floating wind turbines

BELGIUM

	Wind_onshore_BEL	AWE_onshore_BEL	Wind_offshore_BEL	AWE_shallow_BEL
Wind_onshore_BEL	1.00	0.83	0.79	0.79
AWE_onshore_BEL	0.83	1.00	0.82	0.86
Wind_offshore_BEL	0.79	0.82	1.00	0.95
AWE_shallow_BEL	0.79	0.86	0.95	1.00

NETHERLANDS

	Wind_onshore_calliope_NL	ERA5_wind_cnshore_NL	AWE_onshoreNL	Wind_offshore_NL	AWE_shallow_NL
Wind_onshore_calliope_NL	1.00	0.92	0.85	0.81	0.84
ERA5_wind_onshore_NL	0.92	1.00	0.83	0.77	0.82
AWE_onshoreNL	0.85	0.83	1.00	0.86	0.90
Wind_offshore_NL	0.81	0.77	0.86	1.00	0.96
AWE_shallow_NL	0.84	0.82	0.90	0.96	1.00

GERMANY

	Wind_onshore_DEU	AWE_onshore_DEU	Wind_offshore_DEU	AWE_shallow_DEU
Wind_onshore_DEU	1.00	0.77	0.62	0.65
AWE_onshore_DEU	0.77	1.00	0.77	0.81
Wind_offshore_DEU	0.62	0.77	1.00	0.96
AWE_shallow_DEU	0.65	0.81	0.96	1.00

Figure E.2: Correlations between offshore wind technologies for countries where there is only potential for fixed-bottom offshore wind