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PAPER

The potential role of airborne and floating wind in the North Sea region

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Abstract

Novel wind technologies, in particular airborne wind energy (AWE) and floating offshore wind turbines, have the potential to unlock untapped wind resources and contribute to power system stability in unique ways. So far, the techno-economic potential of both technologies has only been investigated at a small scale, whereas the most significant benefits will likely play out on a system scale. Given the urgency of the energy transition, the possible contribution of these novel technologies should be addressed. Therefore, we investigate the main system-level trade-offs in integrating AWE systems and floating wind turbines into a highly renewable future energy system. To do so, we develop a modelling workflow that integrates wind resource assessment and future cost and performance estimations into a large-scale energy system model, which finds cost-optimal system designs that are operationally feasible with hourly temporal resolution across ten countries in the North Sea region. Acknowledging the uncertainty on AWE systems' future costs and performance and floating wind turbines, we examine a broad range of cost and technology development scenarios and identify which insights are consistent across different possible futures. We find that onshore AWE outperforms conventional onshore wind regarding system-wide benefits due to higher wind resource availability and distinctive hourly generation profiles, which are sometimes complementary to conventional onshore turbines. The achievable power density per ground surface area is the main limiting factor in large-scale onshore AWE deployment. Offshore AWE, in contrast, provides system benefits similar to those of offshore wind alternatives. Therefore, deployment is primarily driven by cost competitiveness. Floating wind turbines achieve higher performance than conventional wind turbines, so they can cost more and remain competitive. AWE, in particular, might be able to play a significant role in a climate-neutral European energy supply and thus warrants further study.

1. Introduction

Wind energy is regarded as one of the pillars of the global energy transition. The most recent IPCC report lists wind and solar energy as the most significant potential contributors to net emission reductions by 2030 [1]. Wind turbines are a mature technology; however, most global wind resources remain untapped because conventional wind turbines can not reach them [2]. Therefore, new technologies are being developed to open up additional wind resources. Here, we assess two major emerging wind energy technologies and their potential role: airborne wind energy (AWE) systems and floating offshore horizontal-axis wind turbines, as illustrated in figure 1. We do so with a case study for the North Sea region, which has substantial wind energy potential due to its frequently high wind speeds, relatively shallow waters, and proximity to leading world economies that have stated their commitment to the clean energy transition. In addition, as a first of its kind, our study focuses on the system integration benefits of these new technologies. This is paramount to gaining political traction and funding that may enable and accelerate their large-scale implementation.

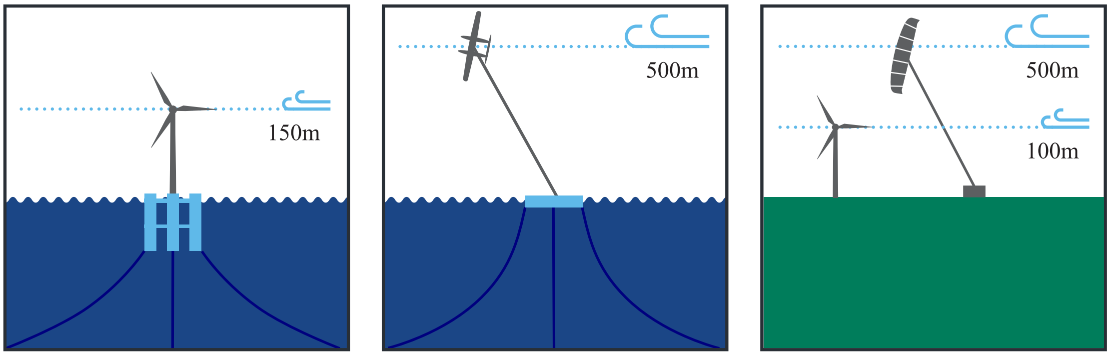

Figure 1. Floating offshore horizontal-axis wind turbine (left), floating offshore fixed-wing AWE energy system (centre), and onshore soft-wing AWE system with a wind turbine for reference (right).

AWE systems extract energy from wind by using flying tethered devices [3]. The fundamentals of AWE have been described in the literature for many years [4, 5]. In short, AWE systems operate at altitudes of 250–600 m, significantly higher than the hub heights of conventional wind turbines. At these altitudes, there are less variable and stronger winds [2]. Consequently, AWE systems enable unlocking vast wind resources that have never been harnessed. On top of that, the operational altitude can be adjusted to harvest the best available wind resource at every moment of the day. Combining these properties leads to a potentially high annual energy generation [6, 7]. Due to this high resource potential and degree of flexibility [8], AWE systems are considered very promising for integration into the energy system [9, 10]. Furthermore, AWE systems require fewer raw materials than conventional wind turbines to generate a given amount of energy [11, 12]. Thanks to this low material use, the costs and environmental impact could be significantly lower once economies of scale are achieved [13]. So far, the focus for future upscaling of AWE systems has been on reference designs [14, 15] and performance estimation [16], as well as on creating maximal economic value [17]. Maximal capacity factors found in earlier site-specific studies reach values from 54% [8] up to 68% [18]. A recent International Renewable Energy Agency report refers to AWE systems as a 'potential game-changer' [19]. However, there are many challenges to overcome, such as reliability, robustness, automation, and regulation, before this potential can be realised. Social acceptance and noise are also still being researched.

In this paper, we consider only ground-generation AWE systems because they are currently the most mature and dominant technology [3, 20–22]. Ground generation is based on using a kite or wing tethered to a generator on the ground [23]. The operation of a ground-generation system consists of two operational phases: the traction phase, where the tether is reeled out and generates electrical energy at the ground station, and the recovery phase, where the kite is reeled in using a fraction of the generated electricity [3]. The first commercially available systems have a nominal power of 100 kW [24] and 200 kW [25], respectively, but path studies consider future systems with nominal power of up to 5 MW [26].

Although many studies focus on the technology, studies on its impact on the energy system are scarce. By comparing AWE systems to conventional wind turbines in terms of power production, variability, and location-specific conditions, a recent study [27] found a substantial similarity between the two overall, although noting a better performance of AWE in high wind shear areas. A follow-up work by the same authors [28] extended the analysis to look at the integration of AWE in the electricity system of four representative countries with very different wind patterns. The work found that the economic added value of AWE is highest when applied in limited amounts and at poor wind sites. Finally, a recent study [8] investigated the use of AWE as part of off-grid energy systems and found that AWE can reduce off-grid energy system costs significantly compared to conventional wind turbines.

While AWE exploits additional wind resources by going higher up in the atmosphere, another option is to deploy conventional offshore wind turbines further out in the ocean, away from the coast, using floating turbines. The current deployment of conventional, fixed-bottom offshore wind turbines is limited to a maximum water depth of roughly 60 m. Because floating wind turbines have the potential to operate in water depths up to 1000 m, this opens up numerous high-wind resource regions across the globe [29]. Some of the most significant potential markets in the world have very few shallow-water offshore locations [30], but also in existing offshore wind areas, the added potential is substantial. In Europe alone, the technical potential for floating wind is estimated at 4000 GW [31, 32]. 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 (further away from land); for instance, a pilot project in Scotland reported a record annual capacity factor of 57% [33]. Because of the higher energy yield, it is estimated that floating wind turbines can achieve lower LCOE than current fixed-bottom offshore wind turbines by 2030 [34]. Floating wind turbines are deemed essential for policymakers to consider to unlock the potential for offshore wind globally [35]. Many case studies have been done on feasibility [36], preferred platform type [37], as well as multi-criteria evaluation [38], and energy system scenario studies [39]. Moore *et al* [40] investigated the potential by 2050 of floating wind turbines in the UK using an energy system model. In their study, the authors assumed that the LCOE of floating wind turbines is higher than that of conventional wind turbines. Still, their results showed that floating wind turbines could lower total energy system costs. This resulted from floating turbines' more constant wind generation patterns, reducing the system's need for storage and balancing compared to conventional offshore wind turbines.

To assess the system-wide potential of both AWE and floating wind turbines, we develop a novel modelling workflow that encompasses wind resource assessment, future technology performance estimation, and integration into a high-temporal-resolution model of 10 countries in the North Sea energy system based on the Sector-Coupled Euro-Calliope model [41]. The model represents an energy system driven entirely by renewable energy and accounts for all energy-using sectors (electricity, heat, mobility, and industry). This allows us to assess for the first time the potential benefits of integrating onshore AWE systems and floating offshore wind turbines in a sector-coupled energy system spanning several interconnected countries. Moreover, this is the first study to investigate the potential system-wide benefits of offshore AWE systems. Results vary across a broad range of scenarios by varying land availability, weather, and cost and technology development assumptions, identifying which insights are consistent across the scenarios.

2. Methods

Figure 2 shows an overview of our methods. In short, we model hourly-resolved wind time series and power curves for our technologies of interest, which are then combined into hourly capacity factors. Next, we determine the spatial deployment potential in moving from a single device to a wind farm and the corresponding wake and operational losses. Finally, we aggregate data obtained for specific locations to country-wide data that can be used in an energy system optimization model. The cost-minimising energy system model is based on Sector-Coupled Euro-Calliope [41]. It models the ten countries bordering the North Sea as a regional case study. The model is fed with technology cost projections from established databases and industry and pilot studies, and with wind resource and power curve data for novel wind technologies [42].

2.1. Wind resource

The well-established and publicly available Renewables.ninja tool [43, 44] is used for offshore horizontal-axis wind turbines. Its underlying wind data is based on the NASA MERRA [45] and MERRA-2 [46] database. The tool converts wind speeds into power output using the virtual wind farm (VWF) model, developed by Ian Staffell [47]. Additionally, the tool validates and bias-corrects the data using the realised output of existing wind farms [48]. The outputs depend on the expected hub height of the turbines. Based on the reference turbine used in this study (2.2), the hub height is set to 150 m [49].

Because AWE systems operate at high altitudes, the Renewables.ninja database, providing data up to a maximum hub height of 150 m, is not a viable option. Instead, we use the ERA5 wind database, covering a wide range of altitude levels. 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 [50]. This interpolated dataset is not well calibrated for surface elevation and, therefore, does not work well for elevated (onshore) land areas. However, this sub-set from the CDS has the advantage of providing fast access to the ERA5 data. Because it represents non-elevated areas well, this dataset is used for offshore AWE.

For onshore AWE, the model-level-based ERA5 hourly data is used instead, which is archived in the ECMWF data archive (MARS) [51]. Unlike conventional turbines, AWE systems vary their operational height constantly. Accordingly, we wish to collect wind speed data at an average operational altitude that approximates the average wind speed over a full flight pattern, which is assumed to be 350 m. We then match this average operational altitude to the closest existing altitude levels in the ERA5 database, leading to an altitude of 334 m, or 975 hPa air pressure.

2.2. Power curves

To provide the expected future performance of AWE systems and wind turbines, the wind resource has to be translated into power output using a representative power curve.

For consistency and fair comparison, the capacity factors of conventional offshore wind turbines and floating wind turbines are computed with the same workflow. The power curve for offshore wind turbines comes from a 15 MW offshore wind reference turbine design from a study by the IEA task TCP task 37 [49].

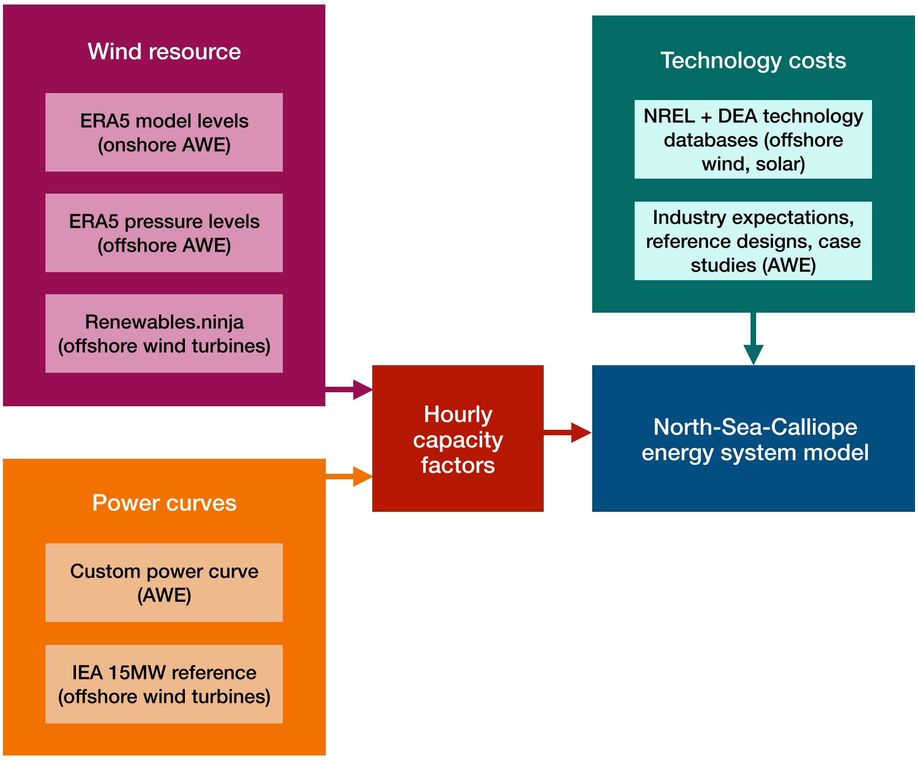

Figure 2. Modelling workflow to compute the inputs for the energy system model.

Similar to the IEA study, we assume that the same 15 MW reference turbine would be used for future floating wind turbines. To achieve this, floating support structures must be scaled up compared to the currently available platforms [52, 53].

We consider two types of AWE systems: a soft-wing configuration for onshore applications and a fixed-wing configuration for offshore applications. The soft-wing system is cheaper to build and operate and is therefore chosen for onshore applications. However, the soft-wing system requires a change of the kite twice a year because of the wear of the material, making it very inconvenient and expensive for offshore applications. Therefore, we choose the fixed-wing system for offshore conditions because these systems are more robust and can last multiple years without replacement. A representative fixed-wing AWE system is simulated, building on models from earlier studies but assuming idealised control for the system. The foundations of our model were introduced in Bonnin [54] and Joshi *et al* [17], and the version used in this study is a work in progress for a separate publication. The power curve is computed using a quasi-steady model [14], which is based on steady-state flight dynamics. The model is implemented as a numerical optimisation problem modelling the system's reel-out and reel-in phases. The model finds optimal operation set-points for a defined system to maximise 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, kite speed, etc. The nominal power is capped at 2.5 MW. Two power curves are used: *Fixed-wing 1* (figure 3), which is based on low costs, and *Fixed-wing 2* (figure 3), which is optimised for performance, but therefore also has higher costs.

Soft-wing kites are in the furthest stage of development of all AWE technologies at this moment. Multiple prototypes have been tested at around 100 kW, and the first products are becoming commercially available. Because of this, metered operational data can be used to determine the power curve of the systems. We can realistically approximate future, up-scaled systems based on these field data. In this study, a 500 kW soft-wing ground-generation system is assumed. The power curve comes from a computationally up-scaled version of a smaller system based on data from Kitepower using a quasi-steady model [14] as described above. The power curve is depicted in figure 3.

2.3. Technology costs

We compute our technology cost assumptions for both floating and offshore wind turbines by 2050 by averaging two extensive databases with cost estimates up to 2050 [55, 56]. For soft-wing systems, the report by BVG Associates on behalf of Airborne wind Europe [13] provides cost estimations up until 2050 that were

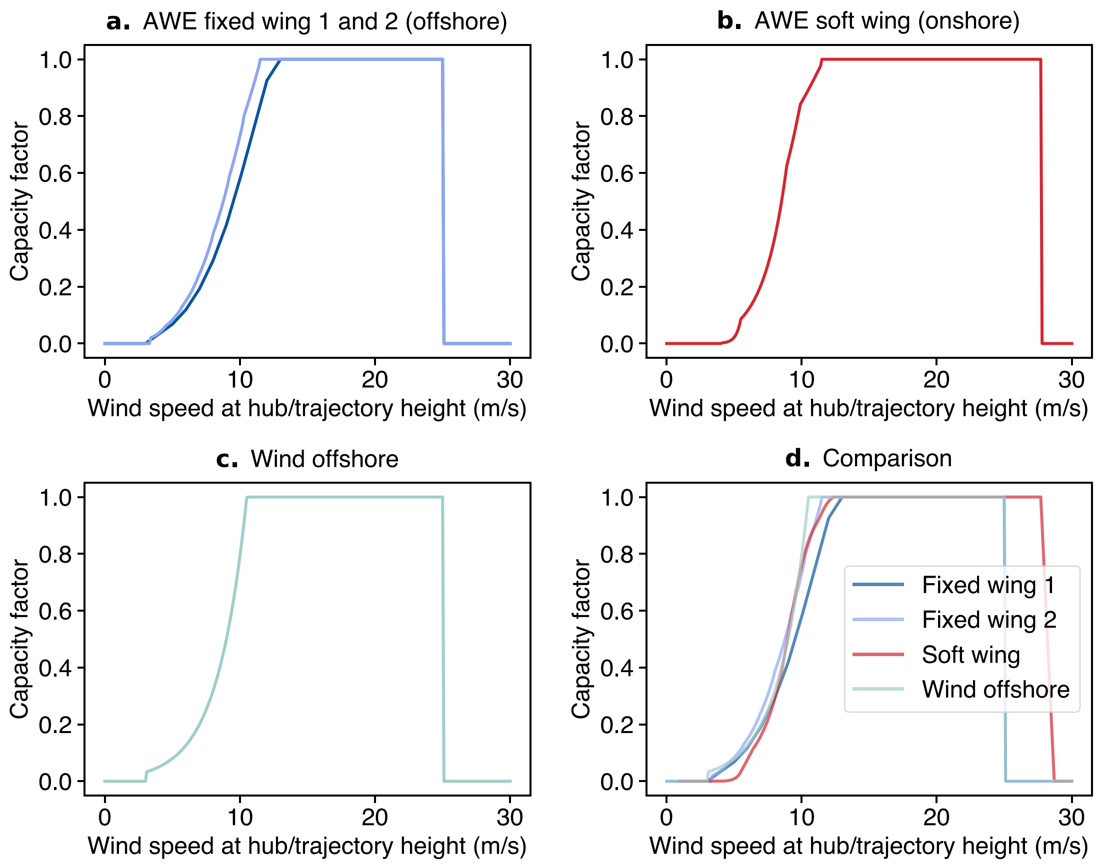

Figure 3. Power curves of considered AWE systems compare with the conventional offshore wind power curve used: Fixed-wing 1 and 2 (used offshore) (a), Soft wing (used onshore) (b), and conventional offshore wind (c). A comparison is also depicted (d), outlining the differences between the different curves.

computed with inputs from major AWE companies. Soft-wing systems are developed further than fixed-wing systems because the latter have higher prototyping and testing costs. Therefore, we adopt cost estimates from ongoing research by Joshi *et al* [57] and Joshi and Trevisi [58], which is based on data obtained from companies, an extensive white paper on AWE by BVG Associates on behalf of Airborne wind Europe [13] and the academic literature. Since the above cost sources for offshore AWE extend only to 2030, a learning curve projects cost assumptions to 2050. Specifically, a 3% yearly cost-learning rate is assumed. This is conservative because fixed-wing systems are still in an early stage of development. All cost assumptions for 2030 and 2050 can be found in the supplementary material table S1. It should be noted that the 2030 costs are not used in the model, but we use them below to discuss the extent to which novel technologies may have become cost-competitive by around 2030.

As described earlier in this report, significant potential for AWE lies offshore in floating applications, for which we must additionally consider the costs of building and maintaining a floating platform. To this end, a conceptual design for a floating platform considered a standard for offshore AWE systems [59] is used. For the cost data, however, the above study refers specifically to a shallow, near-shore area of the North Sea. Therefore, while these data are used directly for our shallow-water AWE (competing with conventional, fixed-bottom wind turbines), an assumed 20% increase in platform CAPEX and OPEX for deep-water applications accounts for their additional installation, maintenance, and development costs.

2.4. Energy system model

We model the North-Sea energy system using the Calliope framework [60]. Calliope is an open-source modelling framework created to build energy systems at high spatial and temporal resolution. By default, the model uses a cost-minimizing linear programming formulation. Previous work introduced the Sector-Coupled Euro-Calliope model [41], which comprises 35 European countries and all energy sectors (electricity, heating, mobility, industry). This work uses a subset of the above model, hereafter referred to as the North Sea Calliope model. It comprises the nine countries that form the North Seas Energy Cooperation and the United Kingdom, which left amid its withdrawal from the European Union. Each country is represented by a single node and is linked to other countries via electricity transmission or the trade of synthetic fuels.

2.5. Spatial potential

Existing assumptions on wind-farm power density are used for conventional wind turbines onshore and offshore. AWE systems will have to be placed in a farm configuration to be integrated at a large scale into the energy system. An important factor in the spacing between AWE systems is safety. A common assumption is to leave one tether length of distance between the ground stations of the AWE systems, leading to a packing density of $1/L^2$.

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 synchronised operation [61] and safety mechanisms that ensure the tethered device gets reeled in quickly when it exceeds the operational limits [62]. Theoretically, the ground stations can be placed closer, leading to a higher packing density. Multiple studies have been done on this topic with limits varying from $1.2/L^2$ packing density [63] to $3/L^2$ [26].

2.6. Land availability

An important constraint in our 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 utilise for wind or solar energy [64].

The theoretical maximal land area is unlikely to be utilised due to policy and social resistance. Hence, based on the recent literature, we make a more realistic assumption, which suggests a maximum of 13.5% of the total theoretically available land area for a case study in the United Kingdom [65]. The resulting area per country is reported in table S3.

Onshore, AWE is assumed to be deployable in the same locations as conventional wind turbines, thereby sharing (and competing for) the same land availability. Offshore, we compute the land availability using the suitable area in the Exclusive Economic Zone of each country [66] and an additional physical limit constraint of 2 MW km^{-2} [67] over the entire area.

2.7. Wake and operational losses

When setting up offshore wind turbines in a wind farm layout, usually a grid, wake effects influence the overall performance compared to a single turbine. This is accounted for by an average wake loss in the deployment of large-scale offshore wind turbine farms of 11.5%, corresponding to a unit efficiency of 88.5% [29]. We assume the availability for both floating and offshore wind turbines to be 97% [68]. This assumption is widely used in literature when assessing the technical potential of wind turbines. For consistency, the same factor is used for AWE systems.

Packing multiple AWE systems effectively requires a wind farm-type layout, similar to what is done for wind turbines. Physical test sites for multiple AWE systems have yet to be carried out simultaneously. Therefore, the only measurements of wake effects come from simulations. The power curves adopted consider the anticipated optimisation of control mechanisms in the future. The same assumption is used to estimate the wake losses. Therefore, only wake-induced losses based on previous work [69] are considered, which leads to a wake loss factor of 0.915 (8.5% wake losses).

2.8. Country wide data

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 representative of the entire country. To accomplish this, several representative points are chosen for each country in the model. These points are in high-potential areas based on average wind speeds and spread throughout the available land area for each considered technology. The locations are identified based on a technical potential study by ESMAP [66] and using Global Wind Atlas version 3.0 (https://globalwindatlas.info). The coordinates for the representative points can be found in tables S5–S7.

The coordinates for deep water AWE correspond to those of floating wind turbines, and identically, we matched the coordinates for shallow water AWE to the coordinates for conventional offshore wind turbines. An overview of competing technologies per region is given in table 1. We average the obtained wind data for all technologies per country. Next, the wind data are matched to the corresponding power curves. This results in an hourly capacity factor per technology for each country. The underlying hourly capacity factors for conventional onshore wind turbines and solar PV technologies come from an original modelling workflow set up by Tröndle *et al* [70].

Table 1. Overview of competing technologies in different regions.

Application	Competing technologies
Onshore	Onshore AWE, Onshore wind turbines, PV
Shallow water	Fixed-bottom offshore wind turbines, shallow water AWE
Deep water	Floating wind turbines, deep water AWE

Table 2. Overview of the tested scenarios.

Technology	Density onshore AWE (MW km^{-2})	Land availability	Weather year	Number of cost projections
Onshore AWE	2, 4, 8	Normal	2013 2014 2015	11
Offshore AWE	2	Normal, Reduced	2013 2014 2015	9
Floating wind	2	Normal, Reduced	2013 2014 2015	11

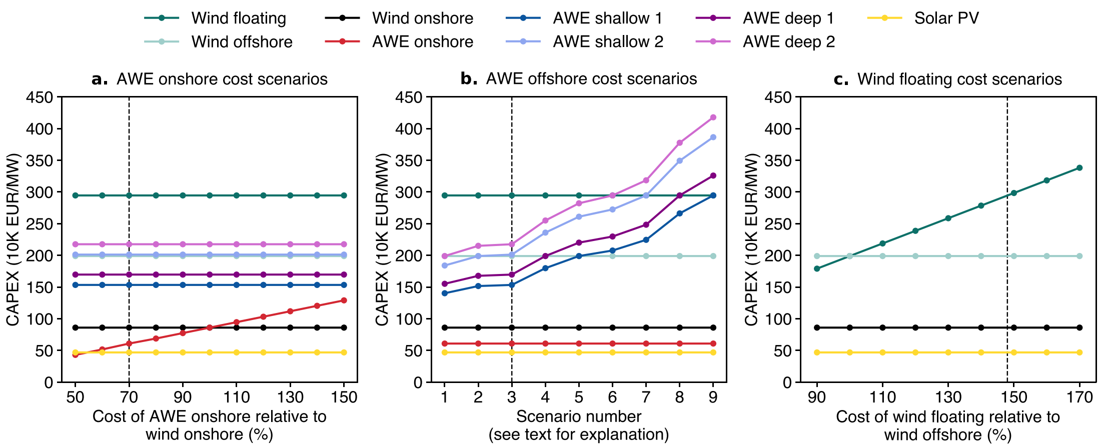

Figure 4. Graphical representation of considered cost variations per technology scenario. A scenario of costs is represented by a collection of vertically aligned (single x-axis value) points on the shown curves. Only the cost for one technology (or group of technologies) changes in each set of scenarios: variations in costs for onshore AWE (a), offshore AWE (b), and floating wind turbines (c). In (a) and (c), the scenarios represent linear cost increments compared to a base case. For the scenarios in (a), we focus mostly on technology costs that are higher than in the base case to appraise the competitiveness of AWE in the near future, in which the optimistic cost reductions assumed for 2050 may not materialise. In (c), no AWE technologies are considered at all to investigate just the role of floating offshore wind, and of cost levels below the base case, because competitiveness was not expected beyond the highest cost level (170% compared to conventional offshore wind turbines). The scenarios in (b), instead, are based on comparing AWE technology costs with competing technologies: In scenario 1, the costs of the most expensive floating AWE technology are matched to the cheapest rival: conventional offshore wind. In scenario 9, the cheapest floating AWE technology matches the most expensive competitor: floating wind turbines. In (c), no AWE technologies are considered at all to investigate just the role of floating offshore wind. The dashed vertical line indicates the reference cost value for 2050, for the technology that varies in the given set of scenarios.

We also impose minimal installed capacities for conventional offshore wind turbines, floating wind turbines, and onshore wind turbines as a constraint. This is done to reflect that plans for renewables deployment are already in place, and novel wind technologies will need to find their space in the framework of an ongoing transition rather than within a green-field system design situation. Therefore, we take the average between the policy goals for 2030 and 2050 goals of the individual countries. When goals beyond 2030 are lacking or unclear, the 2030 goals are used. These minimal capacities are reported table S4.

2.9. Scenarios

The interaction between several new energy generation technologies makes it complicated to analyze the relative merits of each. Appropriate scenarios are used to isolate certain effects and explore the trade-offs of deploying floating wind turbines and AWE in the energy system. This section provides an overview of the scenarios and the associated inputs. Table 2 and figure 4 provide an overview of the considered scenarios. Further explanation is given below.

We assume the base case to be at the initial cost assumptions for offshore wind turbines, AWE, and PV reported in section 2.3. The costs for all other technologies are taken from the original Sector-Coupled Euro-Calliope model [41]. We then form scenario ensembles in which costs are varied for one novel wind technology at a time while keeping all other costs at base-case assumptions (figure 4).

11 scenarios for linearly varying costs of onshore AWE are used to evaluate the trade-offs and effects of implementing onshore AWE systems. A particular focus is on scenarios where technology costs are higher than in the base case. This counterpoises the fact that the chosen onshore AWE cost projections are rather optimistic, with a projection horizon of 2050. Therefore, the upper range of AWE cost scenarios tested here can give insights into the competitiveness of the technology in the near future, in which cost reductions are less substantial. Because onshore AWE has to compete with PV and onshore wind turbines for the same land, the surface power density is an essential driving factor for the potential. To assess the influence, different packing densities are considered: $1/L^2$, $2/L^2$ and $4/L^2$, corresponding to 2 MW km^{-2}, 4 MW km^{-2} and 8 MW km^{-2} respectively (see table 2).

We adopt a similar approach to analyse the effects of offshore AWE in the energy mix. Instead of a linear variation, the AWE technologies are matched to their competitors: conventional offshore and floating wind turbines. In the first scenario (1), the costs of the most expensive floating AWE technology are matched to the cheapest rival: conventional offshore wind. In the last scenario (9), the cheapest floating AWE technology matches the most expensive competitor: floating wind turbines.

Finally, we exclusively evaluate the trade-offs of integrating floating wind turbines by isolating them from AWE technologies. This means that AWE is left out entirely, both offshore and onshore. The costs of floating wind turbines are varied linearly compared to conventional fixed-bottom offshore wind turbines.

Even though land availability is constrained in the model as discussed in section 2.5, land remains abundantly available for onshore renewables. This makes it preferable for the model to over-rely on cheaper onshore generation technologies to meet demand in a cost-optimal way unless marked performance advantages exist for (costlier) offshore technologies. However, most countries aim for offshore energy generation due to its higher societal acceptance. We define scenarios with an even more stringent onshore land availability constraint to reproduce this dynamic and test its impact on results. This also enables a more specific analysis of the trade-offs between offshore wind technologies, which will compete to compensate for the reduced onshore capacity potential. The assumptions for land availability are reported in tables S2 and S3.

We consider three weather scenarios to test the effect of weather on the relative system-wide merits of novel wind technologies. In total, six years of weather years are available from our data set. Three are selected by running the model once for each available weather year and then identifying the two extreme cases and the median case in terms of resulting system cost as a proxy for the ease of matching weather-dependent demand and supply. The highest system costs were found in 2013, 2014 represented a median year, and 2015 led to the lowest system costs.

3. Results

Unless stated otherwise, the scenario results presented in this section are for the median-cost weather year 2014. Results for the other weather years are reported in the supplementary material.

3.1. Onshore AWE significantly outperforms onshore wind turbines

Onshore AWE performs significantly better than conventional onshore wind regarding average capacity factors (figure 5). The most significant difference can be found in France, where AWE onshore systems have an average capacity factor of 48% compared to 28% for onshore wind turbines. The difference in performance is also striking when looking at the load-duration curves. Figure 5 shows the illustrative case of the Netherlands, but the same pattern can be observed for other countries. Onshore AWE has significantly more hours with capacity factors above 50% and more hours where the capacity factor is 0 due to the higher cut-in wind speed. Zooming in on the hourly generation profiles further highlights how the generation patterns of onshore AWE differ from those of conventional onshore wind turbines (figure 5). This is mainly due to the difference in operational altitude. The wind speed onshore significantly increases with altitude due to the reduced effect of obstacles on the ground. As a result, AWE capacity factors are consistently higher than those of onshore wind turbines whenever the cut-in speed is achieved. While onshore AWE and onshore wind generation patterns generally show a strong hour-by-hour correlation, with Pearson correlation coefficients from 0.7 to 0.9 (tables S8 and S9), the magnitude of the capacity at specific moments differs significantly. Occasionally, they can experience anti-correlation. Figure 5 shows moments in which conventional onshore experience a decline in output while AWE does not, such as in the afternoon of April 5th, 2013.

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

Figure 6 shows the outcomes of all the onshore AWE scenarios. We run the cost scenarios defined in section 2.9 for spatial power densities of 2 MW km^{-2}, 4 MW km^{-2}, and 8 MW km^{-2}. The results show that AWE onshore deployment in the model increases dramatically with spatial energy density. With an AWE

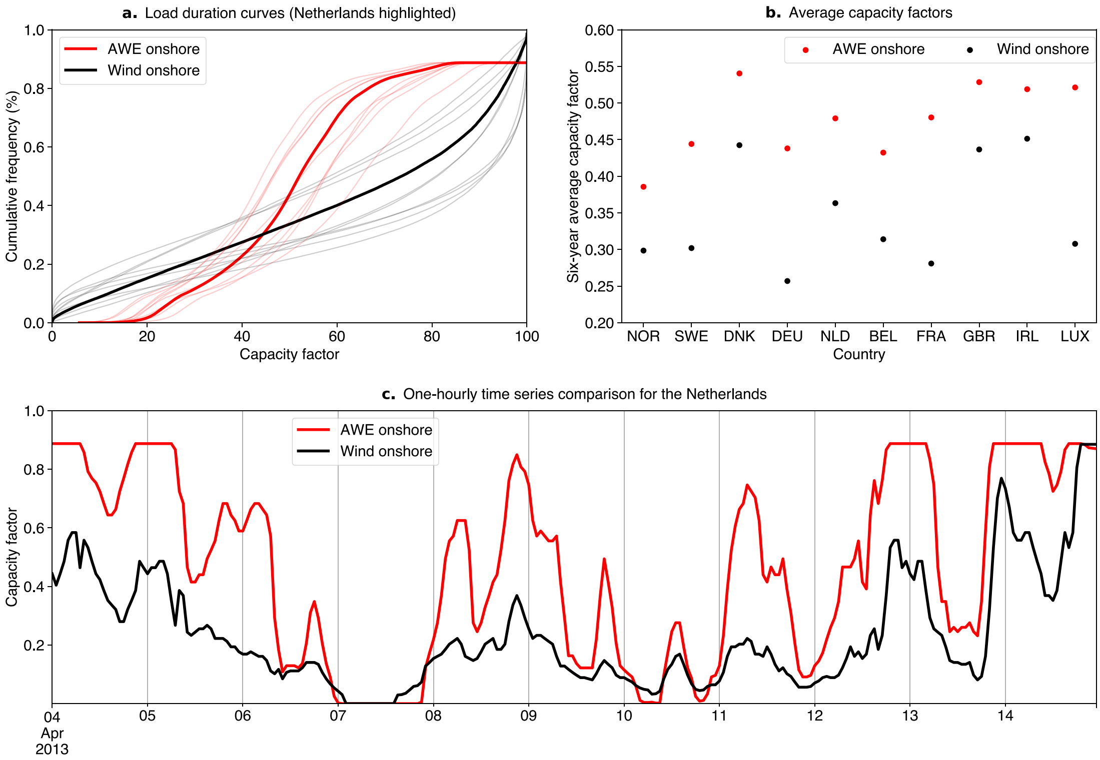

Figure 5. Load duration curves of onshore AWE compared to onshore wind turbines (thick lines representing the Netherlands, lighter lines all the other countries in the model) (a), average national capacity factors over six years (b), and ten days of generation of onshore AWE and onshore wind turbines in the Netherlands, arbitrarily selected among days in which the profile distinctiveness is particularly marked (c).

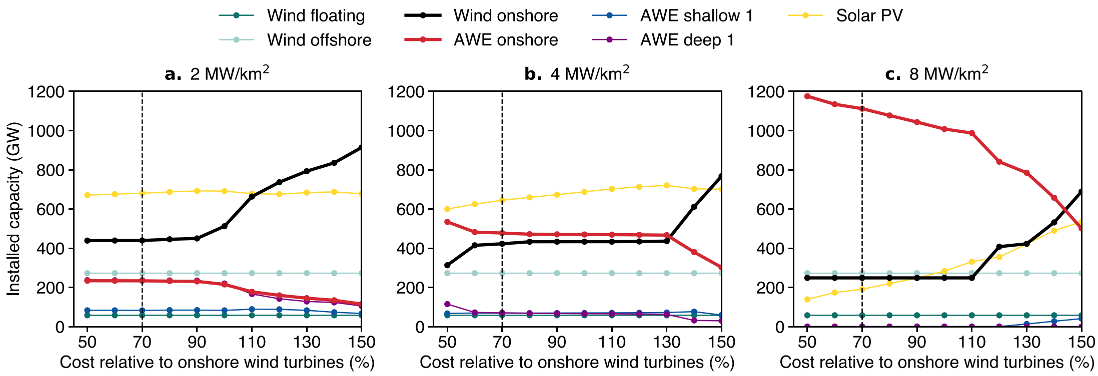

Figure 6. Installed capacity of the main supply technologies in the energy system throughout all evaluated scenarios for the three considered spatial power densities (2 MW km^{-2} (a), 4 MW km^{-2} (b), 8 MW km^{-2} (c)). The capacities of onshore AWE and onshore wind turbines are depicted in red and black, respectively.

energy density of 2 MW km^{-2}, conventional onshore wind turbines are deployed in larger amounts than onshore AWE. When assuming an AWE energy density of 4 MW km^{-2}, onshore AWE, and onshore wind turbines make up a similar part of the energy mix. When assuming that onshore AWE has the same spatial density as conventional onshore wind turbines (8 MW km^{-2}), onshore AWE takes over as the desirable onshore wind technology in the system. At this spatial density, onshore AWE has less installed capacity than conventional onshore wind turbines, which is only in the highest-cost scenario. It is worth highlighting how onshore AWE is always deployed to some extent across all of the evaluated scenarios, including when the costs are 150% of the costs of onshore wind turbines and the power density is at its lowest. In other words, AWE is not entirely excluded from the system design in any of the scenarios. This suggests that AWE brings unique benefits to the system, likely due to the considerably stronger generation patterns previously discussed than those of conventional wind turbines.

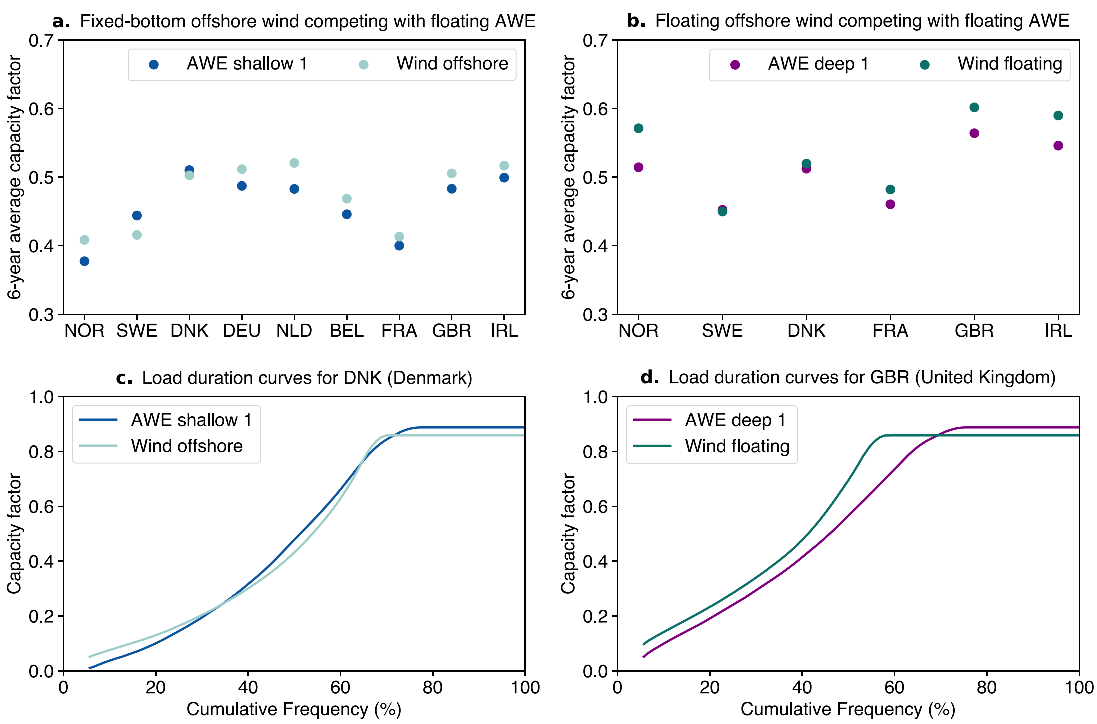

Figure 7. Six-year average nationwide capacity factors for shallow water AWE vs. fixed-bottom offshore wind (a), and deep water AWE vs. floating offshore wind turbines (b), as well as the corresponding load duration curves for Denmark (c) and the United Kingdom (d).

3.3. Offshore AWE has similar generation patterns to offshore wind turbine technologies

When analyzing offshore generation profiles, performances look substantially more similar across competing technologies. As shown in figure 7, 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 illustrative load duration curves in figure 7, with the annotation that floating wind turbines slightly outperform deep water AWE systems. Additionally, the Pearson correlation factor between the capacity factors of competing technologies is above 0.9 for most countries (tables S8 and S9). This substantial similarity originates in very little difference in wind resources at the respective operational altitudes of competing offshore wind turbines and AWE systems. Due to the absence of obstacles, the winds at lower altitudes are more powerful in offshore conditions than in onshore conditions and do not increase much above the 150 m hub height of offshore wind turbines considered in this study.

Throughout all scenarios evaluated in this study, the high-performance, high cost offshore 'fixed wing 2' AWE systems (see figure 3) did not play any role. Therefore, they have not been included in the presentation of the results. Thus, only 'AWE shallow 1' and 'AWE deep 1' are shown.

Due to the similarity in performance and generation observed in figure 7, the deployment of offshore AWE compared to other offshore wind technologies is largely cost-driven (figure S10). For the base-case cost assumptions, offshore AWE is cheaper and thus preferred over rivalling offshore wind technologies. However, for cost levels above the base case, offshore AWE is deployed on a large scale due to higher capacity factors of deep water AWE compared to 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. 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.

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

When comparing floating offshore wind turbines to conventional offshore wind turbines, the difference in performance stands out. Although they are modelled based on the same turbine archetypes, figure 8 shows a marked difference in nationwide capacity factors, except in Sweden and Denmark. The same is visible when

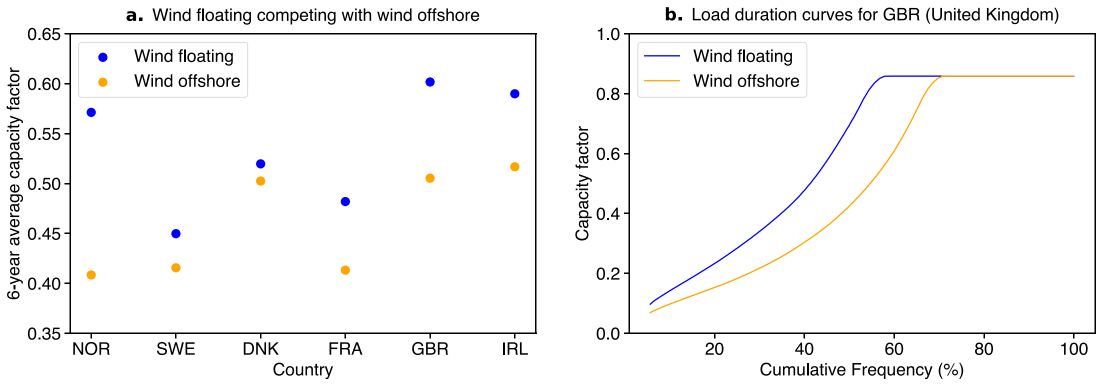

Figure 8. Six-year average nationwide capacity factors for floating wind turbines vs. fixed-bottom offshore wind (a), and the load duration curves over the same six years for the United Kingdom (b).

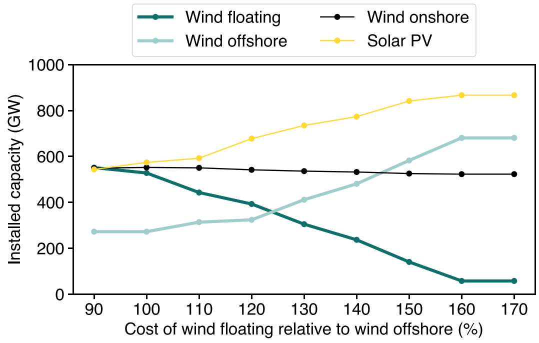

Figure 9. Installed capacities (GW) of wind and solar energy for different cost variations of floating wind compared to conventional offshore wind turbines in the scenario where AWE is left out. Weather year: 2014.

comparing the load duration curves of both technologies. The more significant the difference in capacity factor, the poorer the correlation.

Floating wind turbines are attractive at substantially higher costs than fixed-bottom offshore wind turbines. Figure 9 shows the outcomes of the floating wind turbine scenarios specified in section 2.9 for all three different weather years. We see that the cross-over point between floating wind turbines and offshore wind turbines lies roughly between a 120% and a 130% cost difference. Considering that the same turbine characteristics were taken for floating and conventional offshore wind, the difference in capacity factor is the driving factor in the system-wide preference for floating wind turbines.

Floating wind turbines are deployed in non-negligible amounts already at base-case costs (which are almost 150% of conventional offshore turbines, as reported in figure 4). Nonetheless, their cross-over point of 120%–130% cost difference compared to conventional offshore wind is lower than the base case cost, while increasing costs above the base case leads to the exclusion of floating wind turbines from the cost-optimal system design. This suggests there may be limited room for accommodating worse-than-expected cost developments in the coming years.

3.5. Onshore AWE permits systems with lower capacities and costs

Across the considered scenarios, onshore AWE shows the most significant potential to drive down the overall costs of the energy system, especially when increasing the power density. Compared to the base case scenario without AWE, the system costs experience a reduction between 3%, when taking a power density of 2 MW km^{-2}, and 16%, when the power density is increased to 8 MW km^{-2} (figure S2). This suggests that deploying onshore AWE systems and opening up new wind resources positively impacts the total cost of a fully carbon-neutral energy system. Here, we look at the correlation between onshore AWE deployment and structural changes in the system design to better understand the reasons behind such system-wide cost benefits.

Figure 10(a) shows that the higher capacity factors of onshore AWE result in a lower total installed generation capacity in the system. Additionally, higher shares of AWE systems make converting renewable electricity into e-fuels (by deploying a higher capacity of electrolysers) more cost-effective. This increased

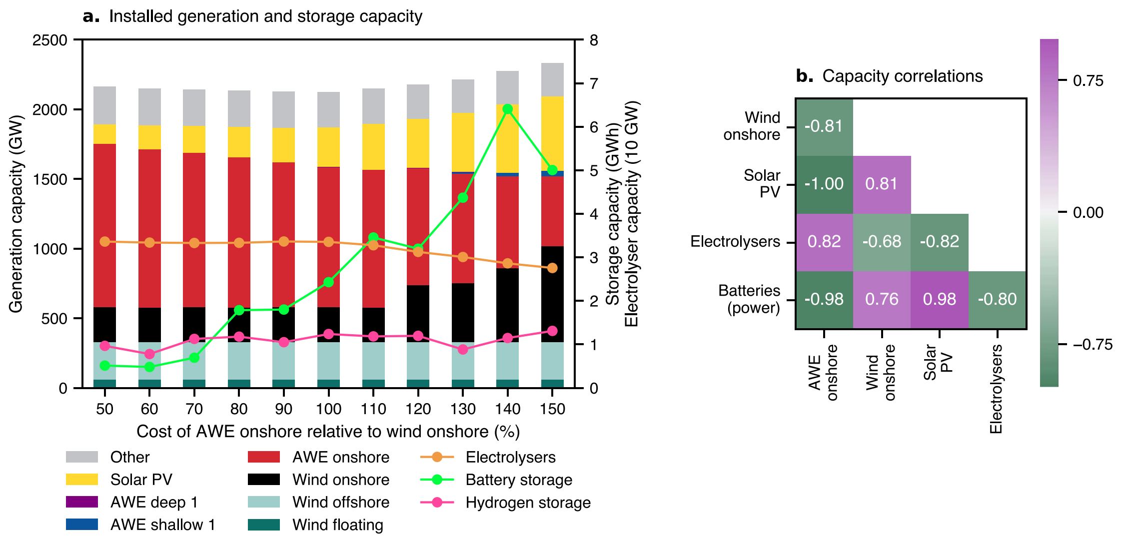

Figure 10. Total installed generation and storage capacities for selected generation and storage technologies for the onshore AWE, land-restricted, 8 MW km^{-2} scenario (a) and the Spearman correlation between the analysed onshore renewable energy technologies (b). 'Other' sums up hydro-power, nuclear power, and bio-fuel & waste power.

cost-effectiveness of converting electricity into e-fuels arises from the seasonal effects in the generation patterns of onshore AWE, which has higher capacity factors in winter than in summer due to higher wind resources. The connection between AWE systems and e-fuels is further corroborated by the analysis of technology deployment correlations across scenarios, which highlight this dynamic as a peculiar feature of AWE systems, not replicated by conventional onshore wind generation (figure 10(b)). Indeed, in higher-cost scenarios where AWE systems become less attractive and are deployed in smaller amounts, they are replaced by a combination of conventional onshore wind and solar energy. Because the system becomes less dominated by wind power, the overall generation is more balanced throughout the year, resulting in short-term storage options becoming more beneficial over large shares of e-fuels. In particular, the increase in solar energy leads to a more diurnal generation pattern, which is then facilitated by an increase in battery capacity.

A similar correlation emerges from the offshore AWE scenario outcomes (figure S10, results for the base case and 2014 weather year): the installed generation capacity decreases when offshore AWE is integrated. When offshore AWE is excluded from the system design in higher-cost scenarios, it is replaced by a combination of onshore wind, conventional offshore wind, floating wind, and PV. Again, the seasonality effects flatten out, and instead, the need for short-term storage (batteries) rises due to the diurnal cycle of solar energy. However, the decrease in system costs for integrating offshore AWE and floating wind turbines is slight (about 2%–3%). The difference is well within the uncertainty margins of the cost, performance, and weather inputs. The difference in system costs for offshore AWE and floating wind scenarios increases when onshore land availability is restricted (figures S10 and S11, results for the 'reduced land availability' cases). However, the absolute system costs compared to the non-restricted scenarios are still relatively small (5%–7%).

4. Discussion

In this study, we focus on the large-scale integration of AWE in the energy system in wind farm-like layouts. From the results, there is a lot of potential for this technology in the future when it is expected that the costs of AWE devices are going to drop. The main deciding factor for this type of application will be the costs and performance since AWE has to compete with existing and mature wind turbine technology. However, due to their non-cost advantages, AWE systems could already be the preferred technology today.

In all scenarios regarding AWE, the cost variations are primarily focused on more pessimistic cost assumptions than the base case. In both onshore and offshore AWE scenarios, the base case demonstrates significant potential for the respective technologies. In the onshore scenarios, AWE even becomes the most system-beneficial technology up until higher costs than onshore wind turbines when the power density is increased. With the cross-over points being at higher AWE costs than expected by 2050, AWE already has the perspective to become competitive at the system scale in the imminent future, possibly as early as the 2030 s.

For offshore AWE, we chose a conservative learning rate of 3% from 2030 onwards. A higher learning rate can bring forward the moment offshore AWE becomes competitive.

From the analysis, it becomes clear that increasing the spatial power density of onshore AWE has the most dramatic effect on system costs across all the considered scenarios (figure S2). 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 (table S1). This implies that the major hurdle towards system integration is not so much the cost of an individual system as 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 the literature already [18]. Similarly, raising packing densities has been the topic of research for some years, as discussed in section 2.5, 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 evidence is yet to come.

Similar arguments can be made for floating wind turbines. The ability to operate in previously unavailable areas allows for fast integration into the energy system, even at higher costs. In contrast to AWE, floating wind turbines are in a further stage of development, and floating wind is already included in national and European energy strategies and extensive subsidy programmes. Therefore, the first commercial projects are being planned, and the technology has already been proven to work at a multi-MW scale through several pilot projects.

4.1. 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* [27], Trevisi *et al* [18], Reuchlin *et al* [8]. The difference between capacity factors for AWE compared to onshore wind turbines that were 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* [2]. The timeline towards cost-competitiveness of AWE for both onshore and offshore applications corresponds to the general anticipation and outlook from the sector itself [3, 13].

For floating wind turbines, the capacity factors were in the same range as identified by Bosch *et al* [29]. The cross-over points between conventional wind turbines and floating wind turbines were distinguished for larger differences in costs compared to Moore *et al* [40], in favour of floating wind turbines. Also, the higher wind resource potential for floating wind turbines is in line with Dupont *et al* [35] and Bosch *et al* [29], as well as expectations by the offshore wind industry [32, 33].

Although uncertainty remains present in potential estimates for emerging technologies, the comparison to the literature demonstrates that the inputs that were used for the energy system model in this study are as plausible as they can be at this point in time. 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 the literature and by the industry. The outcomes of this study confirm the potential of floating wind turbines in a large-scale energy system.

4.2. Limitations

We used a cost-minimising 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 system design as an outcome, which is cost-driven. However, previous work [71] has shown that many alternative feasible solutions exist within a small relaxation of the minimum feasible system cost, which may be more desirable and viable from a societal perspective. This is valid in terms of both technology mix and spatial configuration of renewable power capacity deployment [71].

Furthermore, cost-minimizing solutions may hide from view the uncertainty in assumptions and sensitivity of the outcomes. For instance, an important finding in the offshore scenarios is that deploying offshore wind technologies strongly depends on the assumed available onshore generation potential; if a very large amount of land onshore is deemed socially acceptable for infrastructure deployment, little offshore power capacity deployment becomes necessary. At the same time, when evaluating the system costs with heavily restricted land availability compared to the normal scenarios, costs increase by no more than 10% across all scenarios (figure S2), and such a small difference lies within the uncertainty margin of the cost assumptions. In other words, the difference in system costs (figure S2) is small enough for non-cost factors to give decision-makers the option to prefer offshore wind in practice.

Finally, our study ignores the sequencing of investment decisions to be made when actually implementing the energy transition, focusing instead on the end state of a fully built-out system. If AWE and floating wind are to fulfil some of the possible potential identified here, more work will be needed to identify cost and non-cost barriers to their implementation, as well as suitable policy measures and support schemes to resolve these barriers.

5. Conclusion

This study aimed to identify the main system-wide trade-offs in integrating AWE systems 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, we ran scenarios where the effects of onshore AWE, offshore AWE, and floating wind turbines on the energy system are evaluated individually based on 2050 costs and performance expectations

We find that onshore AWE systems are more cost-effective than onshore wind turbines from a system perspective due to the higher wind resource availability at operational altitudes and an occasionally distinct generation pattern. Due to these benefits, onshore AWE also makes it feasible and cost-effective to have a smaller total generation capacity in the system. Moreover, even though most of our scenarios entailed higher-than-expected cost projections for onshore AWE systems, onshore AWE was never entirely taken over by competing technology and excluded from the least-cost feasible system design. This indicates that onshore AWE devices provide unique benefits to the system and could become economically viable before 2050, potentially even in the early 2030 s. We identified the main limiting factor towards a large roll-out of AWE in its spatial energy density; if the spatial density is increased, onshore AWE can substantially improve the total system costs.

When evaluating AWE offshore, it is clear that the performance and generation pattern of shallow water AWE and deep water AWE are almost identical compared to conventional offshore wind and floating wind, respectively. Due to the high similarity, competitiveness is almost entirely driven by costs. At the system level, deep water AWE systems are 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 distinguish themselves from conventional offshore wind turbines by a clear increase in capacity factor. Floating wind turbines can operate in deeper waters, usually further away from the shore, unlocking high wind resource areas. As a result, the technology is preferred at costs of 120%–130% relative to conventional offshore wind turbines, reducing the overall installed capacity required and the costs of the system.

This work constitutes 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 peculiarities. Our key findings align with expectations based on earlier studies and anticipation within the industry. However, follow-up research is necessary to validate our outcomes further and provide more detail and context.

The main recommendations for future research include assessing the possible non-cost benefits of the considered technologies and more detailed studies. Many aspects are hidden from view when modelling focuses on cost, yet they play a role in the decision-making process. Other important aspects to consider may be the perceived visual and noise impact of AWE systems compared to conventional turbines and the additional benefit AWE systems may have in terms of reduced raw material requirements. Finally, it would be important to analyse more in detail the spatial deployment potential of AWE systems, for instance, homing in on the sub-national regions of a specific country and detecting sites where the wind resource is too poor for conventional wind turbines but sufficient to make AWE economically viable.

Data availability statement

The energy system model is available at https://github.com/calliope-project/North-Sea-Calliope-AWE-floatwind/. The Calliope framework on which this model is based is being developed in the open on GitHub (https://github.com/calliope-project/calliope) [72].

The data that support the findings of this study are openly available at the following URL/DOI: https://github.com/HiddeVostudelft/Datacollection_AWE-floatwind.

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