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Opinion

Investigating Alternative Application Ranges for Floating Offshore Wind

Mareike Leimeister

Department of System Technology, Fraunhofer Institute for Wind Energy Systems IWES, 27572 Bremerhaven, Germany; mareike.leimeister@iwes.fraunhofer.de

Abstract: The current technological developments within the offshore wind industry reveal a trend towards larger wind turbine MW-classes for both bottom-fixed and floating support structures. Furthermore, bottom-fixed designs are modified and enhanced to also serve deeper offshore sites. Apart from these technological developments, another trend of a competitive nature, related to politics and other stakeholders, can be observed: ever-higher targets are specified for offshore wind energy, while national offshore water areas are limited and divided among various stakeholders in terms of their use. This situation raises the following questions, which are discussed in this paper: 1. Should and could floating offshore wind be extended to shallow-water regions? 2. What benefits can be gained when going beyond traditional floating wind technologies, and what does this mean in detail? 3. What are the motivations, challenges, and solutions for coexistence options? The investigations reveal that floating solutions are more than just options for supporting offshore wind turbines at very-deep-water sites. By extending the traditional application ranges of floating wind turbine systems and going beyond traditional floating offshore wind technologies, additional benefits can be reaped, and worldwide climate and renewable energy targets can be met in harmony with other stakeholders.

Keywords: shallow-water floating wind; floating offshore wind turbines; offshore renewable energy; multi-purpose systems; coexistence; co-use

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1. Introduction

The current technological developments in the offshore wind industry show an increasing trend in the wind turbine MW-class, already going beyond 15 MW. Regarding the support structures, the traditional borders for their water-depth-dependent areas of application are relaxed, as bottom-fixed support structures are pushed to be suitable for even deeper water depths. Thus, for example, a jacket support structure is expected to be more cost-competitive than floating technologies up to water depths of even 90 m [1], which is significantly beyond the currently deepest bottom-fixed foundation installation at the Seagreen Wind Farm at 58.6 m water depth [2].

Simultaneously, there is a political development with regard to climate protection measures. Thus, there are various different regional, national, and international targets for expanding renewable energy technologies, and all are aimed at reducing greenhouse gas emissions with the final goal of becoming climate neutral. Europe, for example, seeks a share of 40% renewable energy in 2030 as it wants to be 'fit for 55' in 2030 with 55% reduced net emissions compared to 1990 [3]. Until 2050, it is expected that there will be up to 450 GW of offshore wind capacity required [4]. Having such high targets in various countries worldwide to be achieved within a similar time frame and considering the significant increase in energy demand expected for the next decades (i.e., from less than

3000 TWh in 2024 to around 6800 TWh in 2050) [5] places high demands on industries, infrastructure, and various other stakeholders involved.

With these technological and political developments happening at the same time, the question arises as to how both can best be reconciled and how they can be mutually beneficial. In such situations with challenging requirements, it is sometimes useful to think open-minded and a bit outside the box. Floating offshore wind (FOW) is already seen as a promising technology. But what if one goes beyond the traditional application range of this relatively new technology? What if not only bottom-fixed wind turbine systems can be deployed in even deeper waters in the future, but also FOW turbines can be utilized in shallow-water areas? What if the understanding of the concept of an FOW turbine system is softened and expanded? And what about the other stakeholders interacting with the FOW industry?

Thus, in this paper, these questions are addressed, and three different alternative application ranges for FOW are investigated. Section 2 starts with the elaboration of whether FOW should and could be extended to shallow-water regions. Going even further, the motivation and solutions for rather futuristic floating wind applications beyond the traditional FOW concepts are assessed in Section 3. Finally, coexistence options for FOW turbines with other stakeholders and potential mutual benefits are discussed in Section 4. The findings for the three different alternative application ranges are comparatively discussed in Section 5 and concluded in Section 6.

2. Shallow-Water FOW Applications

The first question on the topic of shallow-water FOW applications is approached by initially (Section 2.1) investigating the motivations and advantages. A more detailed assessment of the question follows in Section 2.2 by defining and analyzing different feasibility criteria.

2.1. Motivation for and Advantages of Shallow-Water FOW

Contrary to the development seen in bottom-fixed wind turbine systems, there are various motivating and advantageous aspects for pushing the application range of FOW also towards shallow-water areas:

- Environmental aspects:
  Overall, FOW turbine systems exhibit less impact on the environment compared to bottom-fixed systems. Only anchors, which are small compared to the dimensions of bottom-fixed support structures, need to be embedded into the soil. The installation comes with very low noise pollution. Furthermore, the anchoring can be fully removed after the operational lifetime of the wind turbine system, meaning that no structure remains under the seabed after decommissioning.
  However, FOW turbine systems need to be moored to the anchors. Depending on the floater technology and corresponding mooring system type, there is an environmental influence that should not be neglected in some cases. FOW turbine systems with conventional semi-submersible or spar-buoy floaters are commonly moored with catenary mooring lines. These require large footprints, as long parts of the mooring chain are lying on the seabed before being connected to the anchors. Furthermore, in operation, the chains are not only resting on the seabed but also lifted up, lowered down, and moving over the seabed, which additionally disturbs the ecosystem of the seabed in this huge radius around the actual position of the FOW turbine system. If taut or semi-taut mooring systems are utilized, not only is the required footprint significantly reduced, but there is also no further environmental impact due to any catenary mooring line lying on or moving over the seabed. Taut solutions are directly related to tension-leg platforms. However, there are also alternative floating technology solutions—even semi-submersible or spar-buoy types—that use semi-taut mooring systems.

- Aspects regarding installation, operation and maintenance, and decommissioning: The installation is quick and rather silent, while the decommissioning is simple and complete. During operation, there are fewer and relatively uncritical scour issues compared to bottom-fixed support structures due to the smaller dimensions of the embedded structures. If FOW turbines are located in shallow-water areas, operation and maintenance work as well as heavy-lift operations can be carried out with common jack-up vessels, making these operations easier than in deeper waters where floating-to-floating solutions would be required.
- Infrastructural aspects:
  Due to the feasibility of fully assembling the FOW turbine system in a port, existing harbor infrastructure, including onsite heavy-lift cranes, can be used, and no special heavy-lift vessels are required. For the transportation of the fully-assembled FOW turbine system to the offshore location, common tugboats can be utilized. These are relevant aspects for some countries, which, for example, do not yet have any special bottom-fixed offshore wind infrastructure and can also not support both bottom-fixed and floating infrastructure. Thus, it would be more affordable for them to invest only in floating wind, hence using existing infrastructure and utilizing floating solutions for offshore wind deployment. For example, the Polish National Center for Research and Development has already indicated the utilization of FOW turbine systems in the Baltic Sea [6], which, however, demonstrates predominantly shallow water depths in the Polish zone [7].

2.2. Feasibility Criteria for Shallow-Water FOW Solutions

Despite the variety of motivating and advantageous aspects of the use of FOW solutions in shallow-water areas, the examination of technical feasibility is of the utmost relevance. Looking at the general setting of an FOW turbine system (cf. Figure 1), the investigations can be divided into the following three feasibility criteria, which are elaborated on in more detail in the subsequent sections and have already been pointed out as challenges by Henderson et al. [8]:

1. Shallow-draft FOW system designs;
2. Safe system operation;
3. Feasible and functional mooring system.

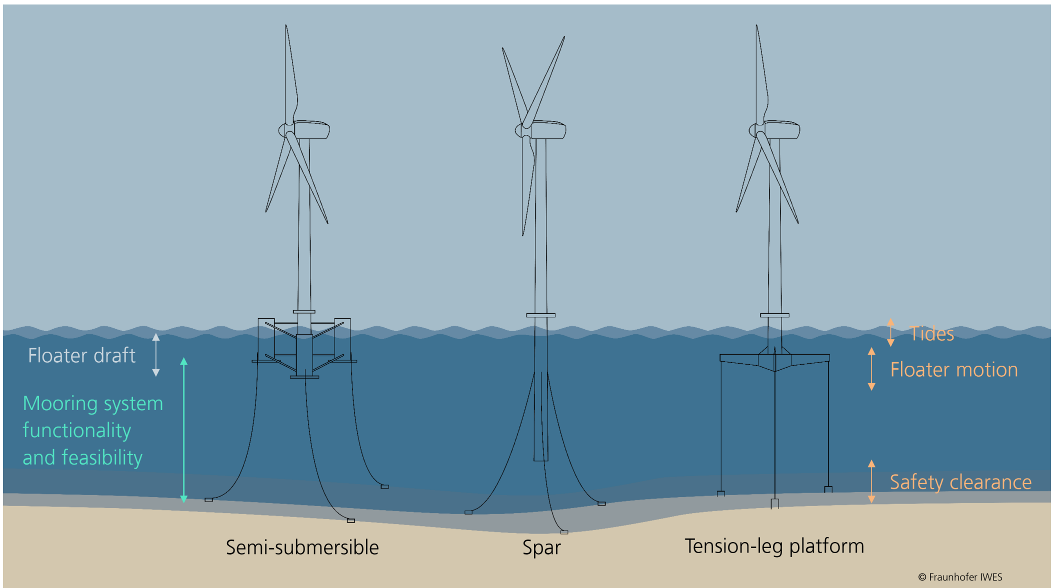

Figure 1. Schematic illustration of the feasibility criteria for shallow-water FOW solutions.

2.2.1. Shallow-Draft FOW System Designs

Shallow-water FOW applications can only be realized with shallow-draft FOW system designs. Thus, spar-type floaters are directly unsuitable due to their deep draft because of the underlying ballast-based stabilization mechanism. On the other hand, floating concepts that have a shallow draft, such as barges, semi-submersibles, tension-leg platforms, or other similar designs, can be regarded as possible in principle. The suitability of tension-leg platforms, however, is questionable due to their stabilization mechanism that is based on the mooring system with vertical tendons, though there are also challenges regarding the feasibility of shallow-water mooring system designs for catenary-moored FOW turbine concepts, as investigated in Section 2.2.3. Nonetheless, there are many floater designs for different wind turbine MW-classes—either conceptualized in numerical models or on paper in patents, or already planned in detail for or deployed in real projects—that exhibit very shallow drafts and/or are intended for shallow-water sites. A summary is presented in Table 1.

Table 1. Existing FOW turbine concepts with shallow drafts and/or utilization at shallow-water sites.

Concept	Turbine Class	Draft	Water Depth
Patent WO 2020/168343 A2 [9]	x MW	≤1 m/MW	
MC021 (Marino Consulting) [10]	2 MW	0.922 m	
Ino 12 (InSPIRE Ph I) [11]	2 MW		30 m
Floatgen/Damping Pool (Ideol) [11,12]	2 MW	7.5 m	33 m
Gicon-SOF [11]	2.3 MW		35 m
Eolink [11]	5 MW		30 m
FloatWind [13]	5 MW	4.27–4.4 m	∼50 m
TH Floater (China Three Gorges) [11,14]	5.5 MW		27–30 m
nezzy^2 Demo/OceanX [11,15]	16.6 MW (2 × 8.3 MW)		40 m
Nerewind^{TM} (DORIS) [11]	10 MW		30 m
Ino 12 (InSPIRE Ph II) [11]	12 MW		30 m
HiveWind [16]	15 MW	8 m	
WindBarge (Green Floating Marine Structures) [17]	15 MW		≤40 m

2.2.2. Safe System Operation

Knowing that there are structural design solutions for shallow-draft FOW turbine systems that allow sufficient clearance between the floater draft and the seabed even at shallow-water sites in the neutral position of the wind turbine system, it needs to be ensured that they also operate safely under the prevailing environmental conditions. Thus, in addition to the floater draft, the floater motion during system operation and the tides at the offshore site need to be taken into account when assessing the feasibility of maintaining the required safety clearance for avoiding seabed contact with the structure even in severe environmental conditions.

As the tides are local conditions that can only be taken into account during the design process of an FOW farm, the determining factor is the motion response of the FOW turbine system, which needs to be reduced [8] and kept as low as reasonably practicable. The most critical motion is the offset in the vertical direction. This can be directly affected with the help of heave plates for a reduced heave motion. However, the roll and pitch motions also contribute to the vertical displacement of the FOW turbine system, whereby the larger the outer dimensions of the floater, the greater the significance of these rotatory movements. Additional features, such as an active ballast system, could help reduce the system's motions in the rotatory degrees of freedom. This may be further enhanced by means of a wave-predictive control strategy.

It is, however, questionable how large the safety clearance between the floating structure and the seabed needs to be, and if it really has to be maintained all the time. There might be some floating system designs that could be suitable for allowing seabed contact, at least during severe environmental conditions. Conceivable would be pendulum-stabilized floater concepts, such as Stiesdal's TetraSpar [18] or Saipem's HexaFloat^{TM} [19], if the respective component (i.e., the pendulum) is designed accordingly. In events of higher vertical motions of the FOW turbine system or very low tides, the pendulum might rest on the seabed. This also affects the overall dynamic response characteristics of the floating system, which would then rather represent something like a tension-leg platform. Once the conditions have calmed down, the pendulum will be lifted up again. For such an approach, detailed investigations of structural and environmental impacts are certainly required.

Another aspect of safe system operation is the motion and position of the power cable. It is expected that the general approach of reducing the overall FOW turbine system motion by the above-described measures counteracts the disadvantageous aspect of having a shorter distance between the hang-off point at the floater and the seabed. However, detailed motion-based investigations are required, especially for the more ambitious approach with an allowance for seabed contact.

2.2.3. Feasible and Functional Mooring System

The design of a well-performing mooring system for shallow-water applications that experiences, at the same time, reasonable line tension was already declared one of the long-term research challenges in wind energy as part of the research agenda 2016 by the European Academy of Wind Energy [20]. The main reasons for that are highlighted in the following [21]:

- For shallow-water applications, the distance between the fairlead and the seabed is quite small. This implies a short suspended mooring line length and, subsequently, a low inherent pretension. To counteract this, larger chains are required.
- Any horizontal motion of the FOW turbine system causes, in shallow-water applications compared to deep-water ones, a larger mooring line length to be lifted from the seabed. This results in greater mooring line stiffness and tension and, consequently, a risk of line break. At the same time, the higher mooring line stiffness induces higher eigenfrequencies of the horizontal, translatory motions of the FOW turbine system, which ultimately leads to a stronger response to difference-frequency wave loads.
- For FOW wind turbine systems at shallow-water sites, there is a higher risk of mooring line stretching due to a loss of the shape of a catenary line. The associated risk of vertical loads on anchors can be prevented by having a longer part of the mooring line resting on the seabed. This, however, entails the disadvantage of having an even further increased footprint compared to deep-water, catenary-moored FOW applications.

Furthermore, an ever stronger focus is being placed on biodiversity. Thus, nature-positive mooring system solutions are listed as one of the action points in the strategic research and innovation agenda for 2025–2027 by ETIPWind [22].

However, there are ongoing investigations in research studies and joint industry projects that are addressing these challenges and looking for solutions for feasible and functional mooring system designs for shallow-water FOW applications:

- One opportunity, for example, is to use polymer springs, which are stiffer under low loads but react more flexibly under higher loads. The inclusion of polymer springs in FOW turbine mooring system designs for shallow-water applications would enable a reduction in peak tension of around 50 to 60%, which in turn would also significantly reduce mooring line fatigue loads [23,24].

- Another approach is to use alternative mooring concepts, such as mooring chains with additional clump weights and/or buoys, as well as synthetic fiber ropes without or with additional buoys and, optionally also, clump weights. These mooring configurations are expected to be more suitable for shallow-water FOW turbine systems compared to conventional chain mooring. For environmental reasons (cf. Section 2.1), mooring concepts utilizing synthetic fiber ropes are preferable, as these solutions fall into the category of semi-taut mooring systems [21].
- Last but not least, optimization-based techniques are proven approaches within design development tasks and are also very promising for mooring system design applications. Very sophisticated optimization routines allow consideration of various design variables, such as structural and geometrical characteristics of the mooring line; the mooring line design (e.g., general mooring line type or additional components); the number, distribution, and arrangement of the mooring lines; and the fairlead and anchor positions. Within the mooring system optimization, prevailing environmental conditions and the actual FOW turbine system are taken into account as well [25–28].

3. Applications Beyond Traditional FOW Technologies

Rather opposite to the previous potential technological development of utilizing floating support structures for offshore wind turbines in shallow-water areas is the proposition of going beyond the traditional FOW technologies and not having any mooring system at all. This idea, rather, corresponds to something like energy ships harvesting renewable energy while sailing over the open sea. A more detailed explanation of the meaning and motivation for such applications beyond traditional FOW technologies is given in Section 3.1, while some conceptual solutions are presented in Section 3.2.

3.1. The 'What' and 'Why'

In the category of such rather unconventional FOW turbine applications fall unmoored floating renewable energy conversion systems, which harvest different renewable energy sources and may also include conversion and storage utilities. These systems operate autonomously, potentially in large fleets, and have implied a weather routing system to follow suitable wind trajectories over the ocean and avoid severe environmental conditions.

Even if wind turbines—either the traditional horizontal-axis turbines with three blades or also other types, such as Flettner rotors or sails—are elementary to these floating renewable energy conversion systems, they are not always used for harvesting the energy out of the wind for conversion into electrical energy. In some cases, the wind turbine systems only serve for propulsion and navigation of the system on the open ocean. There are, however, also solutions where the wind loads on the wind turbine are utilized both for rotating the rotor and producing electrical energy as well as for moving the ship-style system. Any electrical energy generated by the renewable energy harvesting systems is converted and stored onboard. Commonly, electrolyzers are utilized and the storage medium is hydrogen. Hydrogen can then be transferred, for example, to vessels for being transported to the shore. If hydrogen is further processed offshore, it is expected that vessels, container ships, or cruisers can be refueled directly offshore.

The motivations for going beyond traditional FOW technologies are both related to energy security as well as environmental and economic aspects. Such autonomously operating floating renewable energy conversion systems can harness offshore wind energy in international waters and, hence, also open up offshore energy use to landlocked countries. The implicit weather routing system allows for operations with optimal energy yield, while the fact that neither a mooring system nor a power cable to the shore is required reduces the footprint to just the waterplane area of the structure. Furthermore, these unconventional FOW technologies could even be multi-purpose systems, capable of harvesting, converting, and storing different renewable energy sources; serving as an offshore refueling station; or offering further purposes, such as cleaning ocean waters or functioning as research platforms. Finally, they are also suitable for co-use applications.

3.2. Conceptual Solutions

A few concepts or concept ideas for such innovative and unconventional system solutions going beyond traditional FOW technologies already exist and are shortly presented in the following:

- An unmoored, kilometer-wide floating structure supporting a wind farm has been investigated by the National Institute for Environmental Studies, Japan. Additional sails on top of the semi-submersible structure help control the operational route of the floating system [29].
- Within the Wind Hunter Project, a zero-emission sailing technology is being developed. This utilizes wind power for both propulsion and power generation by means of water turbines and also comprises the energy conversion via electrolysis into hydrogen, the storage of the latter one, and the feasibility of recovering the stored energy by means of fuel cells to be used in electric propellers for propulsion if needed. The construction of the Wind Hunter ship is scheduled to start in 2025 [30,31].
- The FARWIND energy system is like a ship that sails autonomously in far-offshore open waters. The propulsion is provided by Flettner rotors and, at the same time, is used for generating power by means of water turbines. This electric energy is converted onboard into hydrogen and further into methanol [32].
- A conceptual design of a sailing renewable energy conversion system has been developed and assessed by Rickert et al. [33]. This could look like a floating structure in the style of a catamaran that supports a wind turbine (and maybe also other renewable energy conversion systems) and has sufficient deck space for electrolyzer and hydrogen storage containers. Navigation, communication, and control systems allow autonomous operation of the system with a focus on optimum energy yield and safe system operation [33].
- An autonomous wind turbine ship is also being developed and tested as a prototype by SAILWINT. This sailing ship is operated by control systems utilizing artificial intelligence. The overall objective is to harness wind energy on the vast open oceans. The electrical energy captured from the wind is converted by means of electrolyzers to hydrogen, which is then stored [34].
- A catamaran-style sailing yacht is being developed by Drift and the construction of the first unit is planned to begin in 2025. The main focus of the British start-up is to provide green hydrogen and benefit harbor areas with huge energy demands especially as well as island nations. The yacht is sailing with the wind. Electricity is produced by water turbines and solar panels and converted by means of electrolyzers into hydrogen. The sailing route is planned and controlled based on artificial intelligence, aiming at an optimal operation [30,35].

4. Coexistence with Other Marine Stakeholders

Another aspect of going beyond traditional FOW technology applications is coexistence. The various interests in ocean space are currently rather competitive, but the demand for ocean space is expected to grow significantly in the next few decades. Thus, to facilitate future needs, a more cooperative approach is needed. Further motivations as well as potential advantages resulting from coexistence approaches are investigated in Section 4.1, while specific co-use and multi-purpose options for FOW technologies with other ocean space stakeholders are presented in Section 4.2.

4.1. Motivation for and Advantages of Coexistence Options

The current situation is that there are various interests in the ocean space by different stakeholders, such as the offshore wind industry, the aquacultural sector, the oil and gas industry, shipping companies, the fishing industry, the military, and the ecosystem. These interests are not always, but most often, competing with respect to the available ocean space. Moreover, however, most of the activities happen rather close to the shore, which significantly narrows down the ocean space that all stakeholders have to agree on and share. This already indicates the need for optimized marine spatial planning. Beyond that, looking at the future needs and interests in ocean areas until 2050, it becomes clear that "'Coexistence is essential' as DNV report shows demand for ocean space will grow 5-fold by 2050" [36], referring to the spatial competition forecast report by DNV [37]. Thus, more and more parties are investigating coexistence options, such as RWE with its innovation competition on floating wind co-use that was launched in 2023 [38].

The coexistence of various ocean space stakeholders may happen in the form of multi-purpose systems or co-use concepts. Such options are not only essential, as foreseen, but also bring advantages: Any solution for coexistence enables the shared use of logistics and infrastructure required by the individual stakeholders involved. This allows a more efficient utilization of vessels, equipment, and manpower and ultimately has a positive impact on overall costs. Beyond this, the systems combined in multi-purpose platforms share structural components. This not only reduces material demand and costs but also lowers the effort for maintenance and repair work as fewer structures need to be inspected compared to independent individual platforms for each application.

4.2. Coexistence Options for FOW and Other Marine Stakeholders

Of the large number of stakeholders, some are particularly suitable for coexistence with the FOW industry, such as other renewable energy industries, aquaculture, or offshore hydrogen production. Options for multi-purpose and co-use concepts as well as mutual positive influences—in addition to the general advantages highlighted in Section 4.1—are presented in the following.

4.2.1. Floating Wind and Other Renewable Energies

Combining different renewable energies is in general already pursued due to their volatile nature and the fact that they often complement each other well, which facilitates a more stable energy supply. Furthermore, having different renewable energy systems together on one floating structure yields a higher power output per platform. Suitable and already existing multi-purpose solutions for harvesting more than one renewable energy source are, for instance, a combination of FOW turbines and wave energy devices, such as the InSPIRE [39] or W2Power [40] concepts, or FOW and photovoltaics as implemented in SOcean [41]. So-called Floating Modular Energy Islands (FMEIs) [42,43] even go beyond the combination of different renewable energies and also comprise energy storage systems, which also leads to savings in the broader area of infrastructure, including storage and energy transport. There might be further beneficial effects that still need to be investigated in more detail. It is, for example, conceivable that wave energy converters on an FOW turbine system positively influence the dynamic motions, structural loads, and energy output.

The beneficial effect of having reduced energy in the waves behind wave energy converters is already used for coastal protection and can directly be transferred to co-locating FOW turbines and wave energy converters in an offshore farm [44]. There are, however, also a number of investigations being carried out for co-use solutions of FOW and photovoltaics, both in research [44–46] and industrial plans, such as by Acciona, including offshore hydrogen production as well [47].

4.2.2. Floating Wind and Aquaculture

A conceptual design for a multi-purpose platform for not only FOW and photovoltaics but also aquaculture is proposed and assessed in a research study by Zheng et al. [48]. The authors believe that this combined wind–solar–aquaculture system can be competitive in the future.

In the short term, co-use concepts for FOW and aquaculture are probably more realistic. Aker Solutions [49] already focuses on offshore fish farming and proposes its Aker Solutions Ocean Cage. The company foresees a huge potential for co-locating these cages with offshore wind turbines, as there are synergies between aquaculture and offshore wind: Both need some distances between their single units, one to secure good water quality for the fish, the other to recover good wind quality and reduce wake effects [49].

4.2.3. Floating Wind and Offshore Hydrogen

With FOW technologies, even far-offshore deep-water sites can be exploited. Their economic viability, however, will be limited when the electricity must still be transmitted to the shore via power cables. This is where offshore hydrogen comes in [50]. If the electrolyzer is placed directly on top of the floating support structure for the offshore wind turbine, the additional technological challenge that the FOW industry has to face, namely the dynamic power cable, is thus bypassed. Solutions for such multi-purpose platforms are, for example, the concept by Dolphyn Hydrogen [51] or NereHyd$^{\mathrm{TM}}$ by DORIS [52] and Lhyfe.

However, there could also be a separate offshore hydrogen platform placed within an FOW farm, as pursued by Tractebel Overdick [53] or Acciona with its plans for a floating wind-and-solar hydrogen complex [47]. Such an offshore hydrogen platform could even serve as an offshore refueling station for vessels if the hydrogen is further processed into a fuel that is suitable for ships.

5. Discussion

Having presented and investigated three different alternative application ranges for FOW—i.e., shallow-water FOW applications (cf. Section 2), applications beyond traditional FOW technologies (cf. Section 3), and coexistence with other marine stakeholders (cf. Section 4)—the solutions and findings are hereinafter comparatively discussed. The following three aspects are considered: What are the opportunities of the three different alternative application ranges for FOW (Section 5.1)? To which extent are these feasible (Section 5.2)? And what are the main challenges (Section 5.3)?

5.1. Opportunities

All three different alternative application ranges for FOW presented in this paper have in common that they are solutions helping to achieve the climate targets, meet the worldwide energy demand (even if it is expected to increase significantly in the future), and cope with prevailing boundary conditions and fundamental requirements.

One opportunity is increased environmental friendliness:

- With all solutions, the footprint, seabed contact, and impact on the environment can be lowered compared to conventional FOW turbine systems: If the promising taut or semi-taut mooring line concepts utilizing synthetic fiber ropes are used in the shallow-water FOW solutions the footprint is significantly reduced compared to conventional catenary-moored semi-submersible floaters. Furthermore, compared to bottom-fixed wind turbine systems that are currently deployed in these shallow-water offshore sites, shallow-water FOW solutions have significantly less environmental impact as only anchors need to be installed; moreover, the installation itself is rather quick and silent, and the decommissioning is rather easy without leaving any structure in the seabed. The sailing renewable energy harvesting ships require no mooring lines and no power cable at all. For co-use or multi-purpose FOW solutions, anchors can be shared between the systems, or the ocean space is more effectively used as a reduced number of structures is required for combined solutions [54].

- Some solutions can also contribute to the protection of the environment: If FOW turbine systems coexist with, for example, aquaculture, they demonstrate mutual benefits, as both need distances between the single units. Furthermore, multi-purpose solutions of FOW wind with any other marine stakeholder reduce the material needed as floater and structural components are shared. Similarly, the autonomously sailing renewable energy harvesting systems save material as they combine several systems into one floating structure. Moreover, these systems can also support additional application options, such as cleaning the ocean.
- The combination of different renewable energy harvesting systems, as is achieved when FOW coexists with other renewable energies as well as for the sailing renewable energy harvesting systems, brings mutual benefits to the volatile nature of the different renewable energy sources and, hence, helps counteract climate change and secure the energy supply.

Even if the presented technologies are rather innovative and not yet fully proven and well-known, and hence, some higher costs are expected at that early stage of development, there are some economic benefits that could make these solutions attractive again from a financial point of view:

- Reduced capital expenditure:
  For all solutions that share the floating system or components (e.g., the moorings and anchors)—i.e., applications beyond traditional FOW technologies and coexistence with other marine stakeholders [54]—or no longer require some components at all, as it is the case for the sailing renewable energy harvesting systems in terms of the power cable and mooring system, less material, components, and structures are required, bringing down the capital costs. When co-designing multi-purpose systems, the designs can be optimized in terms of performance, considering the interaction between the comprised systems, and also cost-optimized. The relatively low technology readiness levels of and still fast changes and developments in each individual system technology (especially for wave energy converters but also still for floating wind platforms) even open up opportunities for new and more cost-optimized design solutions for the combined systems [54].
- Reduced operational expenditure:
  Similarly, if systems or components are shared or no longer required at all, logistics and infrastructure can be shared, and the maintenance effort and associated costs are reduced.—On the other hand, higher system complexity might challenge the maintenance (cf. Section 5.3).—Less maintenance may be even required if wave energy converters in coexistence solutions positively influence the dynamic motions of FOW turbine systems, leading to reduced structural loads and fatigue. Similarly, a co-design of combined systems can positively impact the overall system performance and associated operational costs [54]. The sailing renewable energy harvesting systems may lower the operation and maintenance cost even further as the systems can navigate to suitable locations for performing maintenance and repair work. Finally, the main-

tenance of shallow-water FOW solutions is easier—and hence, also expected to be cheaper—than that of conventional deep-water FOW turbine systems that require floating-to-floating maintenance solutions.

- Reduced levelized cost of energy:
  Due to the mutual benefit of combining different renewable energy sources with different characteristics of their volatility, a higher and more constant energy output can be achieved with combined system solutions, such as coexistence concepts or sailing renewable energy harvesting systems. This positively influences the overall levelized cost of energy.

Another opportunity is seen in the broader application ranges as well as higher versatility and diversity. Thus, shallow-water FOW solutions might be more affordable for some countries without specific bottom-fixed infrastructure, as most existing infrastructure (e.g., for common harbor and shipping industry as well as onshore wind) can be used. The application solutions beyond traditional FOW technologies, i.e., renewable energy harvesting systems sailing autonomously over the open sea and in international waters, open up offshore energy use to landlocked countries and enable (remote) island states to be self-sufficient. Finally, multi-purpose and co-use solutions help deal with the limited offshore space and several (competing) marine stakeholders, and hence, allow coexistence in harmony.

5.2. Feasibility

Potentially most interesting is the question of whether the presented solutions are just great, innovative ideas on paper or also feasible in reality. In brief, the feasibility is not doubted; however, the time to market will differ for the three alternative approaches. Considering also the expected challenges that are pointed out in Section 5.3, a rather straightforward realization is seen for coexistence options for FOW with other marine stakeholders, especially in the case of co-use concepts. Multi-purpose solutions as well as shallow-water FOW technologies will need some more development steps and, hence, are expected to be seen afloat in the medium term, while the commercial deployment of sailing renewable energy harvesting systems is estimated to happen rather in the distant future.

All three alternative application solutions are expected to be feasible with respect to the technical concepts:

- Shallow-water FOW solutions:
  In general, the FOW turbine system designs already exist; there is not much difference in the floater design compared to already existing deep-water applications. Also, in terms of the challenge of having a feasible and functional mooring system, this is expected to be feasible, as declared as a research challenge already long ago and many solutions have been investigated and are available, which promises feasible application in shallow-water FOW solutions.
- Applications beyond traditional FOW technologies:
  Even if these might seem to be more complex, they all comprise well-proven technologies and system components (e.g., ship-type vessels, wind turbines, other renewable energy conversion systems, electrolyzers, and hydrogen storage solutions). Furthermore, the idea of sailing renewable energy harvesting systems has been investigated more and more over the last few years, and first pilots and demonstrators have already proved technical feasibility [30,32–35].
- Coexistence with other marine stakeholders:
  Each single system already exists and is a well-proven technology. Furthermore, the designs do not need to be changed at all if co-use concepts are applied. Several

solutions are already available and installed or planned for being deployed and realized in the near future.

However, the concepts do not only need to be technically feasible, they also need to be operational and maintainable. In coexistence solutions, there are only little changes expected compared to the operation and maintenance of the single units. For shallow-water FOW solutions, the operation is expected to be feasible even if some challenges are still prevailing (cf. Section 5.3). Maintenance is even easier compared to conventional deep-water FOW turbine systems (cf. Section 5.1). Similarly, the possibility of unmoored renewable energy harvesting systems to navigate to suitable locations makes maintenance feasible (cf. Section 5.1). For these sailing renewable energy harvesting systems as well as for FOW solutions in coexistence with hydrogen, the transport of hydrogen will be feasible since the same solutions—or even more, due to the site flexibility of the unmoored system solutions for offloading—can be utilized as are currently developed for offshore (bottom-fixed and/or floating) wind.

5.3. *Challenges*

Despite the opportunities and feasibility aspects addressed in Sections 5.1 and 5.2, respectively, there are still some challenges that have to be faced and overcome before the alternative application solutions reach market maturity.

As mentioned in Section 5.2, the systems and technical solutions are expected to be feasible in general; however, some more research and development is needed before final realization. The ongoing investigations on dynamic power cables for FOW turbines has to be continued and intensified. The motion of the power cable due to the moving floating system presents already a challenge for conventional FOW turbine systems, but the significance of this research challenge is increased for shallow-water FOW solutions. For coexistence concepts, however, the question regarding the power cable additionally refers to the compatibility, as different renewable energy harvesting systems demonstrate different power output characteristics [54]. The system motions, on the other hand, challenge also the electrolyzers and electrolysis process happening on sailing renewable energy conversion systems or multi-purpose concepts for FOW and offshore hydrogen. Research is already ongoing but not yet at a stage that it can be directly incorporated based on thorough investigations and elaborations. Another challenge is the combination of various systems and components, as explored in the case of sailing renewable energy harvesting systems and multi-purpose concepts. The combined solution is partially dependent on the actual technology readiness level and development process of each individual system, which can slow down the technological development of the combined system but could also open up room for opportunities (cf. Section 5.1). However, the increased number of components and combined systems also leads to a higher complexity of the combined technology and corresponding challenges with respect to system interactions, control solutions, and interfaces. Finally, the alternative application solutions need to become cost-competitive in the future; thus, also single technologies, such as wave energy converters and their mooring system, have to be further developed to bring down the cost of the individual system components.

A very important aspect that has to be faced and addressed carefully is safety. A safe system operation of technological solutions, posing no risk and no harm to the environment or other assets, is essential. This aspect is seen to be most critical for the sailing renewable energy conversion solutions, as they are the most innovative, shall operate autonomously, rely on artificial intelligence, and have to be fail-safe even in the worst environmental conditions or any failure case. A safe operation is also seen to be challenging for co-use and multi-purpose systems, as higher risks are expected with increasing complexity of the overall system, especially if less mature technologies are integrated. Furthermore, special focus (in the form of further development) has to be put on the mooring system of wave energy converters, as mooring failures are currently very critical and a safety issue [54]. For shallow-water FOW solutions, the requirement of a safe system operation is already pointed out in Section 2.2.2. This aspect needs to be addressed in the design process, considering a safety clearance for avoiding seabed contact. Solution ideas and first approaches exist (e.g., active ballast system or wave-predictive control), but the question is if these are fail-safe and what additional cost (capital and operational—especially for maintenance) they come with. Apart from the challenge of ensuring safety in terms of safe system operation, it is also crucial to guarantee safety with respect to constant power quality. This is especially a challenge for combined systems with multiple renewable energy harvesting technologies of different (and not always directly compatible) power output characteristics. Finally, the renewable energy conversion solutions sailing autonomously over the open sea face another safety challenge: protection against theft and piracy.

The third biggest challenge is seen in regulatory aspects. Above all, for more innovative systems that combine different technologies and stakeholders or operate autonomously and in certain offshore areas, specific legal frameworks for consenting and permitting as well as regulatory frameworks for operation are needed. When FOW technologies coexist with other offshore renewable energies, aquaculture, hydrogen, or further marine industries, several stakeholders have to be regulated at once [54]. Particularly for multi-purpose solutions, the questions concerning responsibility, warranty, insurance, and shared costs for maintenance, among other things, need to be answered. There is also an effect on contracting expected if a certain power quantity or quality has to be guaranteed, but various fluctuating renewable energies are contributing. Similarly, the insurance costs and operational performance are influenced by the complexity of the system—i.e., the higher the number of components and technological systems, the higher the risks—and the maturity of the technologies incorporated. Apart from that, also favorable aspects need to be regulated, for example, if and how non-monetary criteria (e.g., mutual benefits of coexistence options) are considered in the consenting and permitting process. While the different technologies comprised in sailing renewable energy conversion systems might not be counted as competing stakeholders, these autonomously operating and sailing systems have to face other regulatory challenges: the use of the open ocean space and the autonomous operation (potentially by means of artificial intelligence). As the systems sail over the open sea and in international waters, rules applying to the shipping industry might be effective for these technologies as well, whereas adaptations and amendments are likely to be required. The autonomous operation and use of artificial intelligence make a separate legal consideration necessary, especially for safety reasons (cf. preceding paragraph). Nonetheless, these regulatory issues are already prevailing in the automobile industry with autonomous cars; thus, it is expected that the regulatory frameworks that currently are and will be negotiated for autonomous cars can be transferred to autonomously sailing renewable energy conversion systems in the future.

6. Conclusions

This research work investigates future application options for FOW technologies and reveals that these can be much broader and more diverse than are currently common practice. FOW might not only be a solution for deep-water sites where bottom-fixed is no longer technically feasible. Suitable floater concept designs with shallow drafts are reviewed, demonstrating that support structure technologies are already existing for shallow-water applications. However, there are additional development challenges that require a special focus: apart from the floater draft, environmental conditions at the specific site as well as wind turbine system responses and floater motions are crucial for ensuring a safe system operation in compliance with required safety clearances. In addition to that, the design of a well-performing mooring system for shallow-water applications challenges the technical feasibility of shallow-water FOW solutions, but promising approaches are already being investigated. Beyond this opportunity to utilize FOW in shallow-water areas, another alternative application option is presented: Rather unconventional FOW technology solutions, which are not moored and operate autonomously on suitable weather trajectories, might even open up further application ranges where limitations currently prevail. Such systems combine well-known technologies, such as ships, wind turbines, photovoltaics, and hydrogen production, facilitating technical feasibility. The complexity of these systems, on the other hand, and, moreover, the aspect of operating autonomously, challenge the development of such innovative systems with respect to safety and regulatory aspects as well as system interactions. Finally, co-use options or multi-purpose systems are investigated. While some regulatory and security challenges also hold for these systems, their technical feasibility is likely to be higher than that of the autonomously sailing renewable energy harvesting systems, as the complexity and interaction of the systems and system components are less or even very low in the case of co-use solutions. The main benefit of multi-purpose systems and co-use options is that the coexistence of different stakeholders in offshore waters will be enabled while meeting their needs for ocean space so that the renewable energy targets can be achieved in harmony.

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