Remote Renewable Energy Hubs in the High Seas Using Batteries as Energy Vector

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Abstract

In this paper, we propose a new Remote Renewable Energy Hub (RREH) concept for enabling the harvesting of renewable wind energy in the high seas. This new concept of RREH uses unmoored wind turbines for harvesting energy from the abundant far offshore wind resources and brings this energy back to the coast using Lithium-ion NMC955 batteries. We name this new concept Renewable Renewable Energy Hub in the High Seas, or REHS in short. The presentation of this concept comes with a methodology for assessing both the cost of the energy produced and the load factors of this REHS. The methodology is tested using parameter estimates for CAPEX and technical parameters associated with the different components of the whole supply chain estimated for 2030. Following this methodology, we obtain estimates of the cost of electricity originating from the REHS ranging from 160$/MWh to 204$/MWh depending on the distance from the coast, from 150 km to 400 km.

Keywords: Renewable energy, High seas, Remote renewable energy hub, Electricity, Wind power, Energy transition

1. Introduction

Global warming has emerged as a threat to our modern civilization as well as to biodiversity [1]. This climate change is mainly due to anthropogenic emissions of greenhouse gases in Earth's atmosphere [2]. Those emissions could significantly be reduced notably by using substitutes to fossil fuel combustion for energy purpose. In this context, transport and heating systems are in the process of being electrified and renewable energies, particularly solar and wind, are developing rapidly [3]. However, technologies for harvesting renewable energy come with their own set of issues. Among these issues, the low energy density of renewable energy sources necessitates the deployment of infrastructure over extensive areas. Public acceptance and land usage conflicts can limit their implementation in populated areas as well [4].

Issues linked to the exploitation of renewable energy sources onshore can be partly addressed by deploying floating wind turbines in the high seas where wind is abundant and more constant over time than onshore wind [5]. At an average wind velocity higher than inland, wind turbines could have a capacity factor reaching higher values than those usually encountered in current onshore wind farms [5]. High seas territories may thus offer promising red areas to harvest wind energy of higher quality than inland. Moreover, according to international laws [6], vessels from any country are free to pass through high seas, which means that any country with access to the sea could exploit renewable energy in remote offshore locations. This observation suggests that collecting energy in the high seas would allow countries to remain sovereign regarding their energy supply.

Producing electricity in the high seas nevertheless involves numerous technical constraints. Among them, the extreme depths in these areas imply that classical foundations of offshore wind turbines cannot be built. Unmoored Floating Wind Turbines (UFWT) and turbines equipped with suction anchors can address this issue. Moreover, installing energy production facilities in remote locations comes with the issue of energy transportation over long distances. This transport may be problematic, implying large investments and energy losses. In order to transport this produced energy, an alternative to electricity is the use of Power-to-X technologies [7, 8, 9]. Power-to-X technologies consist in producing a given fuel X, for example methane, thanks to electricity and different chemical and physical pro-

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cesses. The produced fuels with electricity are called e-fuels (for electrical fuels). These e-fuels offer several advantages among them: (i) they offer long-term storage possibilities (these fuels are easily storable in comparison with electricity), (ii) they can easily be transported (for example, methane transportation is a mature technology) and (iii) they can be considered as low-carbon fuels. For e-fuels to be considered low-carbon, they must be produced using low-carbon electricity sources, such as solar, wind, nuclear, or hydro power. The sourcing of CO2, which is necessary for some e-fuels, must also rely on this low-carbon electricity [10, 11]. Former research focused on producing energy in remote locations and transporting it with power-to-X technologies leading to the emergence of the concept of Remote Renewable Energy Hubs (RREH), a term first coined in [12].

We note that earlier to the apparition of the concept of RREH, researchers have focused on using long electrical lines/cables for transporting the renewable energy harvested in remote locations to the load. In this respect, it is worth mentioning the Desertec project that aims at importing high quality solar energy from North Africa to Europe [13]. Such projects led to the concept of Global Grid proposed by Chatzivasileiadis et al. [14], which is a globally interconnected electricity transmission network that allows to tackle renewable energy intermittency issues as well as to exploit high quality renewable energy resources. More details about the feasibility of the Global Grid are given by Yu et al. [15].

The specific characteristics of remote Renewable Energy Hubs in the high Seas (REHS) present challenges that make power-to-X technologies and transmission lines complex solutions for transferring energy to onshore locations [16]. These challenges arise due to a variety of factors unique to remote offshore locations. First, for power-to-X technologies, one should note that, even when deployed onshore, these technologies incur significant costs and result in energy losses exceeding 50% [11]. We expect those costs and losses to increase if these technologies are installed on offshore platforms. Indeed, regarding costs, we anticipate that adapting existing Power-to-X technologies for a high-sea environment would be expensive. Additionally, maintenance costs are likely to be significantly higher than for onshore installations. Furthermore, technical constraints imposed by the marine environment, such as those affecting pipes containing chemical components or electrolyzers, could reduce process efficiency. Second, using long transmission lines to transfer this energy to shore would also not be an effective solution. Indeed, unlike classical offshore wind turbines, REHS would be located at a distance of hundreds of kilometers from the coast. Ocean depth would make difficult and economically not interesting to connect with cables these wind turbines to continental electricity grids. Instead of using long transmission lines or power-to-X facilities, electrical energy produced by floating wind turbines could be stored in battery packs (e.g. a standard maritime container filled with batteries). These battery packs would be directly attached to the floating wind turbine. When fully charged, battery packs would be transferred to shore by a means of transport, such as a boat. These means of transportation would also bring back discharged batteries from shore to the floating wind turbines. Therefore, if we apply the taxonomy for characterizing RREH proposed by Dachet et al. [17] to the REHS, the import/export commodity would be uncharged and charged battery packs. We note that this taxonomy also associates a set of locations to a RREH. The type of locations for the hubs studied in this paper differ from those of other RREHs [12, 11] because the hub locations are offshore rather than onshore.

In this paper, we describe and analyze an REHS that allow to harvest wind energy in the high seas and bring this energy to shore by means of Lithium-ion NMC955 battery packs. Figure 1 represents the proposed REHS composed of the three main blocks: production, transportation and delivery. The rest of the paper is organized as follows. In Section 2, we describe the REHS, as well as the different components used in it and its characteristics. In Section 3, we introduce the methodology to estimate electricity cost and load factors related to this REHS. In Section 4, we present and discuss the electricity costs and load factors derived. Finally, Section 5 concludes the paper and provides future research directions.

2. Remote renewable energy hubs in the high seas

In this section, we describe the components, associated costs and energy losses of the proposed REHS based on 2030 cost and properties estimates for UFWT and batteries.

As illustrated in Figure 1, the REHS consists of three parts: production, transport, and delivery. The production hub harvests renewable energy in remote offshore locations, after which the energy can be transported to shore and finally delivered to the electrical network.

In this proposed REHS, the production part consists of Unmoored Floating Wind Turbines (UFWT), which produce electrical energy. This energy is stored in battery packs located on the floating structure.

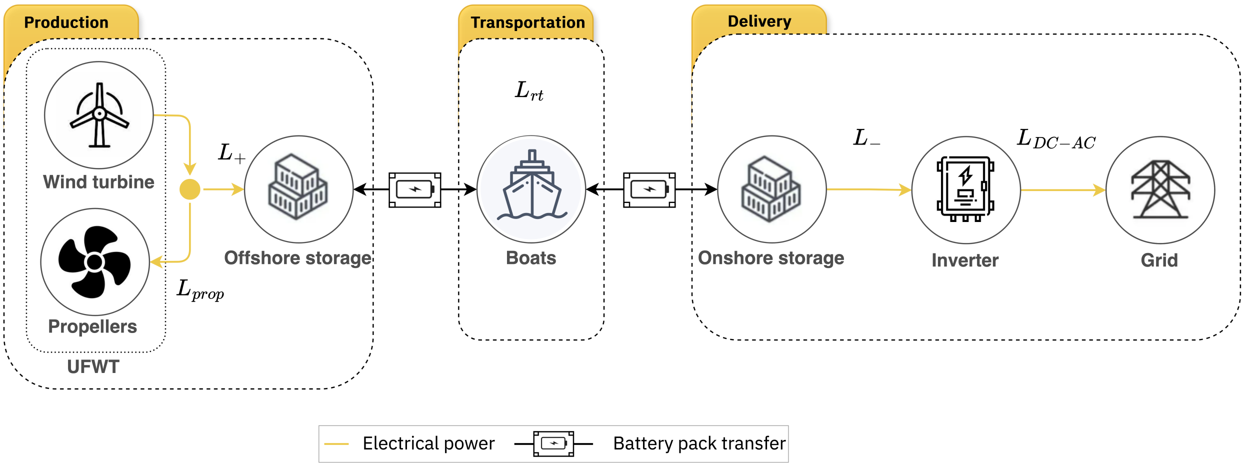

Figure 1: Representation of the components associated with a Remote Renewable Energy Hub in the High Seas, using batteries as the energy vector. The hub is subject to energy losses, which are detailed in Section 2. For example, the symbol L_{prop} denotes the energy consumption of the propellers of the UFWT.

The transportation part involves a boat making round-trips between the production hub and the seaport. Initially, the boat departs from the seaport carrying uncharged batteries. The majority of its cargo consists of discharged batteries, with only a few charged batteries required for the journey to the production hub. At the production hub, the boat uses its cranes to exchange the uncharged batteries for charged batteries from the wind turbines. It then returns to the seaport with the charged batteries. Generally, the boat operates in cycles between the production hub and the seaport, transporting charged battery packs from the production hub and returning with discharged battery packs from the seaport in a continuous loop. At the seaport, cranes are again used to store the charged batteries onshore and replace them with discharged batteries. A cycle consists of bringing charged batteries to the coast and returning discharged batteries to the production hub.

The delivery part refers to the onshore destination where the battery packs are stored to supply electrical energy to the grid through an inverter. Eventually, the onshore charged batteries are discharged to inject electrical power into the grid. Figure 1 illustrates the organisation and components of this proposed REHS.

2.1. Components

Unmoored floating wind turbine

An unmoored floating wind turbine (UFWT) consists in a wind turbine mounted on a floating structure that ensures buoyancy balance and that is connected to propellers to provide stability. Figure 2 provides an illustration of an UFWT proposed by Raisanen et al. [18].

The propellers consume electricity and should be operated at a regime the maximizes the net power generation. In this respect, we refer to the work of Connolly and Crawford [19] that proposes a model of UFWT aiming at identifying the optimalregime of propellers. In the context of our REHS, the wind turbines are assumed to be equipped with battery packs in order to store electricity produced by the turbines. Battery packs would be attached to the emerged bottom of the floating structure in order to facilitate its replacement when loaded on a means of transport. The battery packs are discussed in more details below.

Another aspect to consider is the possibility to make clusters of several UFWTs that would be connected through rigid connections. These connections would ensure stability and could ease the access to the battery packs by having only one location to board them on the boat.. Bae and Kim [20] proposed a detailed analysis for the aerodynamics of such a system and modeled the interactions between UFWTs and the connections. Nevertheless, isolated wind turbines could be easier to manufacture because no connections are needed. An extensive study could be carried out to determine the most cost-effective configuration.

To ensure a better stability, another possibility could be the use of suction anchors. Such anchors would also limit electrical power consumption for propulsion. Suction anchor operation is based on water pressure. The suction anchor first penetrates in the seabed. Then, suc-

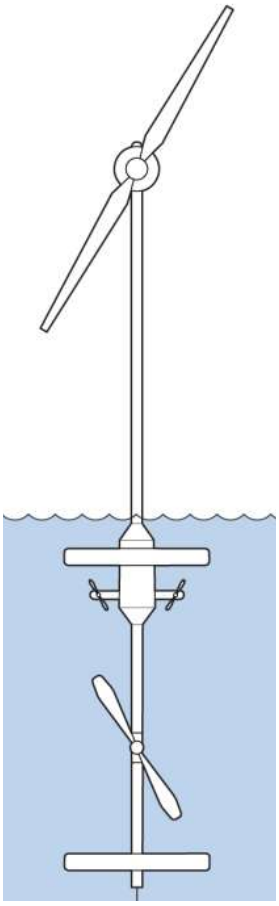

Figure 2: Illustration of an UFWT [18].

tion occurs: a remotely operated vehicle pumps water out of the top suction port, driving the suction anchors deeply into the seabed. Suction anchors can be retrieved by reversing the installation process [21]. More details about the functioning of suction anchors are given by Naji Tahan [22].

An important issue to consider is the potential for severe weather events to cause damage to the production hub. Therefore, UFWTs should be capable of escaping critical zones. This can be achieved through an operational strategy that ensures sufficient electrical energy is always available in the batteries to provide adequate propulsion for the UFWT. Weather forecasts, typically available a few days before a storm's arrival, should be used in such a context to prevent damage to the production hub.

Another possible issue comes from the interactions with ocean waves that could cause a substantial increase in mechanical fatigue of the floating wind turbine structure compared to an onshore wind turbine. We refer the reader to Saenz-Aguirre et al. [23] for more information about this topic.

In the study reported in Section 4, the UFWTs are assumed to be single units equipped with propellers that provide a constant power production with an average capacity factor $CF = 0.50$ for every wind turbine [5]. The CAPEX of the UFWT is estimated at 2.53 M$ per MW, based on [24] 2030 forecast, where only the cost of turbines and foundation are retained. The other costs being related to electrical connections, substations or export cables usually required between the wind turbine and the grid, have been excluded due to the use of battery packs.

Two losses are considered during the operation of UFWT. The first one, called L_{wasted} occurs when operational constraints prevent batteries from being charged during the cycle time. This can happen when they are fully charged or when they are exchanged with discharged ones. In this latter case, the energy that could have been stored is lost because the charging process is interrupted. This energy is therefore wasted.

The second one, called L_{prop} is related to the electrical power produced by the UFWT consumed by the propellers. The ratio of the electrical power consumed by the propellers and the electrical power produced by the UFWT is denoted by the symbol η_{prop}. We will assume that η_{prop} is equal to 0.5. Connolly and Crawford [25], Xu et al. [26] show losses from 20 to 80 % of the power produced by a classic wind turbine. Hence, 50% seems a reasonable assumption given the technological improvement that can achieved until 2030.

Battery Pack

The battery pack is assumed to conform to maritime transport container standards [27]. Battery packs will be located at the base of the UFWT (see Section 2.1). They can be loaded and unloaded onto various modes of transport to travel to the coast, where they will be discharged to supply power to the grid. These battery packs, coupled with a transport method, act as a means of transporting electrical energy, similar to power lines. Of course, using battery packs as an energy vector, can only be credible if we have access to low-cost, energy-dense batteries. In recent years, a sharp decrease has been observed in the cost of batteries. For example, the cost of batteries in 2023 was only 17% of the cost in 2013 [28]. In April 2024, a record low cost of $104.3/kWh was reported for Li-NMC batteries [29]. This decrease in cost is expected to continue according to Orangi et al. [30], who conducted a thorough analysis of the determinants of battery costs and projected that the cost of Li-NMC battery packs could decrease to \$53.4/kWh by 2030 for Lithium-ion NMC955 technology with an energy density of 316 kWh/ton. In this work, we will consider this Lithium-ion NMC955 technology to fill our containers and we will assume as projected cost and energy density for 2030, the values just mentioned. The approximate maximum payload of a maritime container is around 30 tons [31]. We assume that 28 tons are allocated for energy cells and 2 tons for electronics. Therefore, the embedded energy in our battery pack is estimated at 316 kWh/ton · 28 tons = 8.85 MWh.

A standard container costs approximately \$7,000 [27], although the price is expected to be higher due to the specific requirements for handling batteries. However, this increase is considered negligible due to its likely small contribution to the total cost of a battery pack in this study. Consequently, we will use as estimate for the total cost of a battery pack \$53.4/kWh · 8850 kWh + \$7000 = \$479,590.

We note that volume is not a constraint for storing energy in a container. Indeed, assuming a volumetric energy density of 0.260 MWh/m^3 for lithium-ion batteries [32], and given that a container has a volume of approximately 66.71 m^3, it could theoretically store 17 MWh of energy if fully packed with batteries. This is significantly higher than the 8.85 MWh we derived using to the maximum payload constraint.

Charge and discharge losses are denoted as L_+ and L_-, respectively. These losses occur during the charge and discharge of the battery pack. The efficiency of charge and discharge of battery packs is considered constant and equal to $\eta_+ = 95.9\%$ and $\eta_- = 95.9\%$, respectively [11, 32]. The self-discharge of the battery packs is neglected [32].

The lifetime of the battery pack is assumed to be 30 years, based on the Lithium-ion NMC 2030 estimate [32].

Boats

Boats are the transportation method considered for transferring the battery packs (see Figure 2.1). These boats are assumed to be equipped with cranes for loading and unloading the battery packs. They are also assumed to be electric and powered by the transported battery packs. The round-trip energy consumption of the boats is L_{rt}, and their energy consumption depends on their cargo capacity (i.e., the payload they can transport). The energy consumption C of the boat, expressed in MWh of electricity per ton-km, is calculated based on the expression proposed by the Danish Energy Agency [33]. This expression, originally in MJ of fuel per km, has been modified to fit the required units, to take into account the efficiency of an electrical engine and is applicable for boat velocities around 24 km/h. It now reads:

$$C = 2.485 \cdot 10^{-6} + \frac{49}{324 \cdot m}, \tag{1}$$

where C is the consumption of the boat in MWh/ton-km and m is the weight of transported load in tons. The CAPEX of the different boats considered in this study is, by using the model presented in [33], estimated to be equal to \$4,350/ton. The boat is assumed to be equipped with cranes to load and unload the batteries. The cranes consume energy for loading and unloading the batteries. The amount of energy consumed during one cycle is denoted by the symbol L_{crane}. The value of L_{crane} is calculated by estimating the energy required to lift the batteries to a specific height when loading/unloading the boat, see Appendix A.4.

Inverter

At the coast, an inverter is responsible for converting DC to AC current to inject electricity into the grid. The CAPEX of the inverter is neglected, but a loss L_{DC-AC} occurs during this conversion. The inverter's energy efficiency η_{DC-AC} is considered constant and equal to 97% [34].

Cycle Time

The cycle time for the REHS is the time for the boat to bring a battery pack from the production hub to the sea port and back. It includes the travel time from the production hub to the sea port and the time for loading and unloading the battery packs. Time needed to join one UFWT after the other once reaching the hub is assumed negligible.

3. Methodology

In this section, we begin by providing an overview of the methodology used to calculate the energy injected into the grid (Section 3.1). Subsequently, we briefly discuss two metrics - load factors and costs - in Section 3.2 and Section 3.3, which will be used later to compare different REHSs. Further details on the calculations are given in Appendix A.

3.1. Energy injected into the grid

A boat is responsible for the round-trip transportation of batteries between offshore locations and the coast. A cycle involves exchanging batteries at the REHS, returning to the coast, exchanging batteries at the coast, and transporting them back to the REHS. The time required to complete a cycle, denoted as t_{cycle}, is referred to as the cycle time. Each hub studied is characterized by two parameters: the installed power capacity of UFWTs, denoted as P, and the distance d between the hub and the coast. Let E_{cycle} represent the amount of energy produced by the UFWTs during a cycle. This amount of energy can be calculated as follows:

$$E_{cycle} = P \cdot t_{cycle} \cdot CF, \tag{2}$$

where CF is the capacity factor of the installed power capacity at the REHS. Appendix A proposes a strategy for sizing the various components associated with the REHS based on P and d and for estimating the losses and costs associated with each component. From this, the total energy losses per cycle L of an REHS can be derived in a straightforward way by summing up the different energy losses per cycle, see Section 2 for a reminder of the different energy losses. Consequently, the energy injected into the grid per cycle, E_{grid} is estimated as follows:

$$E_{grid} = E_{cycle} - L. \tag{3}$$

We note that from the values of E_{grid} and t_{cycle}, it is straightforward to compute the energy injected into the grid over a given duration.

3.2. Load Factors

One of the main metric to compare different REHS is the load factor π. It is defined as

$$\pi = \frac{E_y}{P \cdot t_y} = \frac{E_{grid}}{P \cdot t_{cycle}} \tag{4}$$

where E_y and E_{grid} is the energy injected to the grid per year and to the grid per cycle, respectively. t_y and t_{cycle} are the number of hours in a year or in a cycle, respectively, P is the power installed in the REHS. To compute how much energy can be delivered to the grid E_{grid} per cycle, Equation 3 is used.

3.3. Cost

The second metric considered is the cost per MWh of electricity injected into the grid. To estimate this cost, we first calculate the sum of the annualized investment costs related to production ($A_{production}$), storage ($A_{storage}$), and transport ($A_{transport}$) in the hub, resulting in a total annualized cost of:

$$A = A_{production} + A_{storage} + A_{transport}. \tag{5}$$

From the value of A, we derive the cost per MWh injected into the grid, c, using the following equation:

$$c = \frac{A}{E_y}, \tag{6}$$

where E_y represents the yearly energy injected into the grid. The CAPEX and lifetimes for production, storage and transport are summarized in Table 1. While this methodology only considers CAPEX for estimating the cost of energy, it accounts for OPEX associated with energy losses, as these are included in the term E_y. For the calculation of annualized costs, a Weighted Average Cost of Capital (WACC) of 7% is used. Note that the computation of total annualized costs excludes the cost of the DC/AC converter located onshore, which we assume could be provided at no cost by the Transmission System Operator. Furthermore, its cost is considered negligible compared to the costs of the boat, UFWTs, and batteries. Similarly, the cost of storing batteries onshore is neglected, as it is assumed to be minimal.

4. Case studies

In this section, the REHS proposed in Section 2 is quantitatively analyzed using some parameters estimates for the costs and physical properties of the components. The results for the costs and load factors presented here are derived using the methodology outlined in Section 3, which is further detailed in Appendix A. The code to reproduce the results is available online[1].

We examine three different cases for this REHS that differ by the parameter d, the distance between the production hub and the seaport. The different distances considered are 150, 400, and 2000 km. In Appendix A, all the details required to derive the sizing of the REHS with respect to the distance and a fixed power installation P = 100MW are provided. Table 2 summarizes the distances and the derived boat capacities.

4.1. Results

Results are presented in Table 2. They show that the closer the production hub from the sea port, the lower the cost. Thus, the optimal configuration in Table 2, is the hub located at 150 km, with a boat cargo capacity of 1,016 tons, and it achieves a cost of \$160/MWh for electrical energy injected into the grid. In terms of load factors, they are similar and ranging from 16.7% to 17.4%. In order of magnitude they are a little bit smaller than load factors observed for onshore wind turbines in Europe [35].

In Table 3, one can see that the share of cost depends on the distance to shore. This can be explained by the fact that the installed wind capacity is fixed at 100 MW; the closer to the coast, the shorter the cycle time. The

[1] https://github.com/VicD1999/REHS/tree/main

Table 1: Technical considerations: lifetime forecast in 2030, Capital Expenditure (CAPEX), velocity of the component.

Component	Lifetime [years]	CAPEX	Velocity [km/h]	References
UFWT	30	2500000 \$/MW	/	[24]
Battery pack	30	54.19 \$/kWh	/	[30] [32]
Boat	20	4400 - 0.0055 m\$/ton	24	[33]

shorter the cycle time the less energy storage needed. Therefore, the closer the UFWTs are to the shore, the more they account for the majority of the REHS's cost, and the farther they are, the more the batteries contribute to the cost of energy. We note that the cost of boats is negligible in comparison with the two other technologies (UFWT and batteries).

In Table 4, the losses that occur during the supply chain are listed. We can see that the losses due to the crane operations are negligible. The biggest loss is related to the propeller to ensure the stability of the UFWT.

Table 2: Results for REHS located at different distances form the shore.

d [km]	m [ton]	π [%]	c [\$/MWh]
150	1016	17.4	160
400	2709	17.3	204
2000	13544	16.7	497

Table 3: Share of costs per component in the REHS.

d [km]	UFWT [%]	Batteries [%]	Boat [%]
150	83.9	16.1	0.0
400	66.1	33.9	0.0
2000	28.0	72.0	0.0

4.2. Discussion

The load factors and cost estimations for the REHS are based on several assumptions previously described. Among them, a proposed assumption is that the time for the boat to pass by each wind turbine of the wind farm can be neglected. In order to determine whether this assumption is reasonable, we made side computations to determine the ratio between the time to pass by each wind turbine of the wind farm, which was previously neglected to study the REHS, and the cycle time, which corresponds to the sum of the travel time from the production hub to the sea port (and vice versa) and the time for loading and unloading the battery packs. This ratio is equal to 0.19%, 0.93% and 2.5% for the distance d = 2000 km, 400 km and 150 km, respectively. Given these estimates, the assumption seems reasonable.

As can be observed in Table 4, the hugest loss of energy is due to the propellers that must ensure spatial stability of the UFWT. Therefore, improvements in order to decrease the energy consumption of this technology could improve significantly the cost and load factors for this REHS. Regarding the energy losses related to L_{wasted}, which are significant, these could be reduced if the operations related to the loading and unloading of the batteries onto the boats were faster. Additionally, we note that the losses related to the cranes are negligible. Finally, improved charge and discharge of the batteries could also have a significant beneficial effect on overall losses, even though battery losses represent only half of those related to ship propulsion.

Larbanois et al. [36] provide cost estimates for e-fuels produced in the Sahara Desert and exported to Europe, ranging from 107€/MWh for hydrogen to 150€/MWh for methane. They are using the same WACC of 7% as in this study. Using the mean exchange rate of 1€ = 1.11\$ from 2023 [37], these e-fuel costs amount to 118.7\$/MWh to 166.5\$/MWh. The cost estimates of electricity exported onshore and produced in production hub at a distance of 150 km, amounting to 160\$/MWh, demonstrate the potential of these REHS to produce energy that could compete, in terms of cost, with low-carbon e-fuels produced onshore in RREH.

International Energy Agency [38] determine the Levelized Cost of Electricity (LCOE) for zero-emissions dispatchable technologies in 2030. For instance, they estimate the cost of electricity produced by hydropower to range from 50 to 130 \$/MWh. The cost of electricity produced in our studied REHS is too expensive and falls outside this range. However, if the WACC is decreased to 5% and we consider a distance to shore equal to 150 km, the cost falls within this range to become equal to 129\$/MWh.

Table 4: REHS: energy losses per cycle in MWh for each operation with respect to the distance to shore.

d [km]	E_{cycle}	L_{wasted}	L_{prop}	L_{+}	L_{crane}	L_{rt}	L_{-}	L_{DC-AC}	E_{grid}
150	673.5	48.5	312.5	12.8	0.0	46.1	12.3	7.2	234.0
400	1796.1	129.5	833.3	34.2	0.0	126.4	32.8	19.2	620.8
2000	8980.6	647.3	4166.7	170.8	0.0	739.5	163.8	92.8	2999.7

The most cost effective configuration considered is the one with the production hub located at a distance of 150 km from the onshore delivery place. In order to further lower the overall costs, that distance could be reduced to just a few tens of kilometers, similar to the range typically reached by conventional offshore wind farms [39]. This would allow to harness wind power near coastal areas where sea depths prevent the building of conventional offshore wind turbines. Production costs of electricity produced from wind power exploitation highly depend on the capacity factor (CF). This CF is associated to the region where the production hub is set up. A CF related to areas close to the coast is likely much lower than the one observed in high seas [40]. Hence, a trade-off emerges regarding this distance to shore and available CF. The distance should be chosen small enough to reduce costs of transportation while maintaining a sufficiently high wind quality.

Additionally, the longest distance to the shore considered (i.e., 2000 km) results in high costs, outside the range of other zero-emissions dispatchable technologies in 2050 discussed above [38]. A potential way to mitigate these costs, particularly those related to the transport, would be to use production hubs in the high seas as recharging stations for cargo ships. Specifically, electric cargo ships could be recharged at sea. Developing offshore recharging facilities could accelerate the decarbonization of maritime transportation. Installing recharging platforms in the high seas could also address the limited range of electric vessels. It is worth noting that a study on offshore charging stations has already been conducted by Yang et al. [41]. Another possibility could be to take advantage of cargo ships that pass close to the production hub while transporting merchandise, using them to transport some of the battery packs.

Furthermore, it is important to acknowledge that the closest distance considered in our study (150 km) is not legally classified as the high seas, according to [42]. Legally, the high seas begin outside the exclusive economic zone (EEZ), which extends up to 370.2 km from the coast. Therefore, a hub located 150 km from shore is likely within the EEZ, not the high seas. This is why we included a distance of 400 km from the coast in our study. However, in certain cases, such as for Belgium, the legal high seas may not be reachable even at 400 km due to EEZ of neighboring countries like the United Kingdom. Consequently, we also considered a distance of 2000 km to ensure the hub is located in the legal high seas. Additionally, for a hub located 150 km offshore, it is unlikely that fixed-foundation offshore wind turbines could be installed due to the depth of the sea. Therefore, the concept of a hub using floating or unmoored wind turbines is more appropriate at this distance. We propose to distinguish between "technical high seas" and "legal high seas," where the former refers to locations where fixed foundations are technically challenging to construct, even if they are within the EEZ.

Lastly, REHS could be further optimized by loading and unloading the batteries onto the boat during periods of low wind activity, provided batteries reach a specified loading threshold. This strategy aims to augment the mean capacity factor (CF) and ensure that battery management operations are conducted under favorable weather conditions.

5. Summary and conclusion

In this paper, we proposed a Remote Renewable Energy Hub in the High Seas (REHS) based on battery packs to deliver electricity generated from wind in the high seas to continental grids. In this REHS, which relies on boat transportation, the cost of injected electricity ranges from 160 to 497 $/MWh, with load factors between 16.7% and 17.4%, depending on the distance to shore, from 150 km to 2000 km.

These costs were determined based on simplified assumptions. As future work, we suggest developing more complex optimization models to identify the most promising energy supply chain. Numerous variables, subject to trade-offs between energy efficiency, delivery time, and cost, need to be considered in determining the optimal configuration. Moreover, this optimization model should help to identify the best places to harvest wind energy in the high seas. Indeed, some locations may exhibit higher capacity factors for the UFWTs than the one considered in this study. However, higher capacity factors could induce higher energy consumption of the UFWTs' propellers due to difficult weather conditions to stabilize the UFWTs.

Technological advancements in the components that constitute this REHS could enhance its cost efficiency. Specifically, we believe that there are two important lines of research in this context. The first concerns the energy consumption of the propellers of unmoored floating wind turbines. These propellers represent the greatest loss in the entire energy supply chain. Therefore, conducting research to improve propeller technology, or find alternatives, such as suction anchors, seems very promising. The second line of research concerns batteries. It is clear that developing batteries that are not only cheaper but also have reduced losses and higher energy density would be very useful in reducing the cost of electricity generated.

In addition to technological advancements, the large-scale deployment of UFWTs depends on the establishment of industrial production lines. This industry could be fully automated, from manufacturing to real-time operation. Large coastal factories could produce UFWTs and deploy them directly at sea upon completion. These turbines would then be capable of autonomously locating and positioning themselves at optimal sites within the production hub.

Moreover, there are several regulatory challenges associated with the deployment of REHS. While international law grants all countries the freedom to harvest renewable energy in the high seas, this could lead to competition over locations with high-quality wind resources. Such overlap may result in legal disputes, which should be carefully anticipated and mitigated to avoid conflict.

Finally, it should be emphasized once again that the estimated costs reported in this paper are for the year 2030. Therefore, if the downward trend in clean technology prices continues beyond 2030, as expected given the trend observed over the past few decades, these costs could continue to decline. A point in time could then be reached when this REHS would have lower costs than conventional electricity generation methods. Furthermore, the implementation of carbon pricing mechanisms could further improve the profitability of these systems, potentially making them competitive with conventional fossil fuel-based electricity producers sooner.

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Competing interests

The authors declare no competing interests.

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Appendix A. REHS efficiency and cost estimates calculation details

In this section, the methodology followed to determine the efficiency and cost estimates for the REHS, represented in Figure 1, is detailed.

Appendix A.1. Sizing the REHS

To determine the efficiency and cost estimates of the REHS, the sizes of its components need to be established. These components include the wind farm's installed power (P), the mass of battery packs required to store the produced energy, and the cargo capacity of the transport means (*i.e.* the boat cargo capacity). For this study, the wind farm's installed power is fixed at $P = 100$MW. As we will see, the mass of the battery packs and the cargo capacity can be derived from P and the distance between the production hub and the shore, denoted by d.

The time required to travel this distance, referred to as the round-trip time (t_{rt}), is given by:

$$t_{rt} = \frac{2d}{v_{bo}}, \tag{A.1}$$

where v_{bo} is the boat velocity.

Under the assumption that the wind farm has a constant load factor CF during the round-trip time, the maximum energy that could be stored in batteries during this time is equal to:

$$E = P \cdot t_{rt} \cdot CF \cdot \eta_{+} \cdot (1 - \eta_{prop}), \tag{A.2}$$

where P, t_{rt}, CF, η_{+}, and η_{prop} represent the wind farm's installed power, the round-trip time, the wind capacity factor, the charge efficiency of the batteries, and the efficiency of the propeller (i.e., the ratio of electrical power used to stabilize the UFWT).

In this REHS, we assume the batteries located next to the wind turbines have a storage capacity E and, hence, that the wind park can fully charge them during the round trip time t_{rt} assuming a capacity factor CF during this time. From these assumptions, we can derive the mass m of batteries installed at the wind park:

$$m = E \cdot \mu, \tag{A.3}$$

where μ is the battery pack energy density. In this REHS, the total mass of batteries required is assumed to be three times m, as battery packs are needed simultaneously in three locations: (a) at the UFWT, (b) on the boat making the round trip between the hub and the shore, and (c) at the shore, where the batteries discharge energy into the grid.

Moreover, we also assume in this REHS that only one single boat, whose capacity is m tons, will bring in one single trip all the batteries located at the wind farm to the coast. During its trip back, the boat will bring the m tons of empty batteries taken from the coast back to the wind farm.

As summary, one of the main parameter determining the sizing of the system is P. From this parameter and the distance d, the parameter m can be computed using Equation A.2 and Equation A.3. The total mass of the batteries is equal to $3m$ and the cargo capacity equal to m.

Appendix A.2. CAPEX of the REHS

In this REHS, the CAPEX considered includes the costs of production, storage and transportation, corresponding to the UFWT, batteries, and boat. The CAPEX values and lifetimes of these components are provided in Table 1.

For each component i, the annualized cost A_i is estimated as:

$$A_i = \frac{CAPEX_i \cdot w}{1 - (1 + w)^{-L_i}}, \tag{A.4}$$

where $CAPEX_i, L_i, w$ represent the capital expenditure of component i, the lifetime of component i, and the WACC, respectively.

From this generic equation Equation A.4, we can specify the production costs, $A_{production}$, expressed in \$/year, are defined as:

$$A_{production} = \frac{p_w \cdot P \cdot w}{1 - (1 + w)^{-T_w}}, \tag{A.5}$$

where p_w, P, T_w, w represent the price per MW of UFWT, the installed capacity, the lifetime of the UFWT and the WACC, respecticely.

Similarly, storage costs, $A_{storage}$, expressed in \$/year, are defined as follows:

$$A_{storage} = 3 \cdot \frac{p_{ba} \cdot m \cdot \mu \cdot w}{1 - (1 + w)^{-T_{ba}}} \tag{A.6}$$

where $p_{ba}, m, \mu, T_{ba}, w$ represent the price per MWh of the battery, the mass of batteries in the REHS, the energy density of the batteries, the lifetime of the batteries, and the WACC, respectively. The factor 3 is related to the sizing assumption that battery packs are required at three locations: the UFWT, the boat, and the delivery place.

Transportation costs, $A_{transport}$, expressed in \$/year, are defined as follows:

$$A_{transport} = \frac{CAPEX_{bo}(m) \cdot w}{1 - (1 + w)^{-T_{bo}}}, \tag{A.7}$$

where $CAPEX_{bo}(m), T_{bo}, w$ represent the CAPEX associated with a boat of cargo capacity m, the lifetime of the boat, and the WACC, respectively.

The total annualized CAPEX, A, is derived as the sum of the annualized production and transportation CAPEX:

$$A = A_{production} + A_{storage} + A_{transport} \quad . \tag{A.8}$$

In our calculations, a WACC of 7% is used.

Appendix A.3. Number of cycles per year

For computing the number of cycles per year, we assume, as done earlier, that a single boat is responsible for transporting the batteries between the production hub and the shore.

Cycle time

Here, we are interested to know the time required for a fully cycle of the boat, called cycle time, that can be defined as the time between two successive arrivals of the boat at the port.

We assume that this cycle time, t_{cycle}, is equal to:

$$t_{cycle} = t_{rt} + t_{lu}, \tag{A.9}$$

where t_{rt}, t_{lu} correspond to the round-trip time defined in Equation A.1, and the sum of loading/unloading time. This time t_{lu}, can be estimated as: $t_{lu} = 4rm$, where r, m correspond to the time for loading and unloading the batteries on the boat per ton and the mass of batteries, respectively. The factor 4 accounts for the following steps performed in the production hub and at the coast: (i) battery packs are first unloaded from the boat (ii) battery packs are loaded onto the boat. We note that half of the time of t_{lu} could have been used to charge additional batteries. But this would not influence much the results since, for all the hubs studied in this paper, t_{lu} which depends on the battery sizing parameter m accounts for less than 3% of the round-trip time t_{rt}.

We note that by using this expression for the cycle time, we neglect the time required for the boat to pass by each UFWT in the production hub of the REHS.

Number of cycles per year

The total number of cycles the boat can complete in a year, n_c, is estimated by dividing the total number of hours in a year by the cycle time:

$$n_c = \frac{t_y}{t_{cycle}}, \tag{A.10}$$

where t_y represents the total number of hours in a year and t_{cycle} the cycle time expressed in hours.

Appendix A.4. Energy losses

In this subsection, we will estimate the different losses per cycle alongside the supply chain. In the production units, that is composed of UFWTs, there is first a waste of energy called L_{wasted} that occurs because the batteries cannot be charged during the period that corresponds to their loading and unloading onto the boat. Additionally, there is a loss of energy in the propellers, L_{prop}, required to stabilize the UFWTS when the wind turbines produce electricity. We will also consider a loss of charge L_+ when charging the batteries. When leaving the platform the batteries contain an amount of energy E. This energy will incur a loss of L_- during discharge for any use. When loading and unloading the batteries onto the boat, both in the production hub and at the coast, a loss L_{crane} is considered. Once on the boat, part of this energy E is used to power the boat for its trip to the coast and later back to the production hub. This loss for the round trip is called L_{rt}. The batteries arrive onshore, where they are discharged into the grid until enough energy remains in the batteries to lift them back onto the boat and for the trip back to the production hub. The energy injected into the grid will undergo an additional loss, L_{DC-AC}, to convert from DC to AC current.

Discarded Energy

The batteries will be fully charged after the round trip time t_{rt}, see Equation A.1. Hence, the energy produced by the UFWTs during the loading/unloading time t_{lu}, see Equation A.9 will be discarded. This corresponds to an amount of energy L_{wasted} equal to:

$$L_{wasted} = P \cdot t_{lu} \cdot CF. \tag{A.11}$$

P, t_{lu}, CF are the wind farm installed power, the loading/unloading time and the capacity factor, respectively.

Propeller energy consumption

Part of the energy produced by the UFWTs, instead of being stored in the batteries, is lost in the propeller. This loss is expressed as

$$L_{prop} = P \cdot t_{rt} \cdot CF \cdot \eta_{prop}, \tag{A.12}$$

where P, t_{rt}, CF, and η_{prop} represent the wind farm's installed power, the round-trip time, the wind capacity factor, and the fraction of the electrical power produced by the UFWT which is consumed by the propeller.

Energy losses when charging

A charge efficiency of η_+ is considered during battery charge [32], resulting in a charging loss of:

$$L_+ = P \cdot t_{rt} \cdot CF \cdot (1 - \eta_{prop}) \cdot (1 - \eta_+), \tag{A.13}$$

where P, t_{rt}, CF, and η_{prop} represent the wind farm's installed power, the round-trip time, the wind capacity factor, and the fraction of the electrical power produced by the UFWT which is consumed by the propeller.

Discharge energy losses

A discharge efficiency η_- is considered during battery discharge [32]. Our system is designed so that when leaving the platform with the energy E, the battery will arrive again at the platform with a level of energy equal to 0. Hence the discharge losses are equal to:

$$L_- = (1 - \eta_-) \cdot E, \tag{A.14}$$

where E is the amount of energy stored in the batteries.

Crane energy consumption

We assume that every time a battery is loaded on a boat or unloaded from a boat, it needs to be lifted to a hight h that we will chosen as being equal to 30m. Hence, since we have a mass of battery m that needs to be lifted four time to this height over a cycle, we assume that the crane energy consumption over a cycle is:

$$L_{crane} = 4 \cdot m \cdot g \cdot h \cdot (1/\epsilon_{elec}) \tag{A.15}$$

where m is the mass of the battery packs transported, g is the gravitational acceleration, h is the lifting height and ϵ_{elec} is the efficiency of the electrical motors of the crane.

Boat energy consumption

The energy consumption for the round trip transportation can be evaluated based on

$$L_{rt} = 2d \cdot m \cdot C, \tag{A.16}$$

where C is defined in Equation 1, m is the mass of the battery packs transported, and $2d$ represents the round-trip distance (twice the distance from the hub to the shore).

Conversion energy losses

Energy losses occur during the conversion of electricity from DC in the battery packs to AC for injection into the grid, with an efficiency η_{DC-AC} assumed. This results in

$$L_{DC-AC} = (1 - \eta_{DC-AC}) \cdot (E - L_- - L_{rt} - L_{crane}), \tag{A.17}$$

where this loss applies only to the net energy output of the battery. Additionally, it is indirectly assumed that both the crane and the boat use DC electric motors.

Appendix A.5. Net electricity export per cycle and per year

Due to all the losses considered in Appendix A.4, only a part of the energy stored in the batteries per cycle, E, is injected into the grid, denoted as E_{grid}. From this energy injected into the grid, we derive the annual energy export.

Net electricity export per cycle

Therefore, during one cycle, the net energy brought to the shore, accounting for all losses, is given by:

$$E_{grid} = E - L_{crane} - L_{rt} - L_{-} - L_{DC-AC}. \tag{A.18}$$

Annual electricity export

The annual energy transported to the shore, E_y, in MWh/year, is calculated as:

$$E_y = E_{grid} \cdot n_c, \tag{A.19}$$

where n_c is the number of cycles per year, as computed in Appendix A.3.

Appendix A.6. Price per MWh

The cost per MWh of electricity injected into the grid can be derived using the annualized cost of the REHS, A, computed in Appendix A.2, and the annual energy transported to the shore, E_y, calculated in Appendix A.5. The price per MWh is expressed as:

$$c = \frac{A}{E_y}, \tag{A.20}$$

where c represents the cost per MWh of electricity delivered to the grid.

Appendix A.7. Load factor of the REHS

The load factor of an REHS, π, a metric representing the use of the installed power capacity over a year, is given by:

$$\pi = \frac{E_y}{t_y \cdot P}, \tag{A.21}$$

where E_y is the annual energy transported to the shore, t_y is the number of hours in a year, and P is the installed power capacity at the hub.

Appendix B. Variables definition

Table B.5: Constants used for cost and load factors estimates of the REHS. Values taken from: [5, 43, 29, 44, 32, 33, 26, 34, 24, 45, 46].

Constant	Name	Value	Unit
v_{bo}	Boat velocity	24	km/h
μ	Battery pack energy density	207	kWh/ton
p_{ba}	Battery pack price	105.196	\$/kWh
η_+	Charge efficiency	0.959	-
η_{DC-AC}	DC-AC conversion efficiency	0.97	-
η_-	Discharge efficiency	0.959	-
ϵ_{elec}	Electric motor efficiency	0.9	-
r	Loading rate	$2.4 \cdot 10^{-4}$	h/ton
η_{prop}	Propeller efficiency	0.5	-
p_w	UFWT cost	$2.5 \cdot 10^6$	\$/MW
CF	Wind capacity factor	0.50	-
w	Weighted Average Capital Cost (WACC)	0.07	-
P	Wind farm installed power	100	MW
t_y	Number of hours in a year	8760	h

Table B.6: Parameters that change across the different distances from the production hub to the shore considered.

Parameter	Name	Unit
$CAPEX_{bo}$	Boat capex	\$/ton
d	Distance between the production hub and the shore	km
n_c	Number of cycles in a year	cycle
m	Cargo capacity / total mass of battery packs	ton
A	Annualized CAPEX cost	\$/year
C	Transportation consumption	kWh/ton-km
t_{cycle}	Cycle time	h
t_{rt}	Round trip time	h
t_{lu}	Time for loading and unloading batteries on the mean of transport	h