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A Literature-based Survey

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Original research article

Risks, strategies, and benefits of offshore energy hubs: A literature-based survey

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A R T I C L E I N F O

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A B S T R A C T

Offshore Energy Hubs, also called Energy Islands, are intensively discussed to become a key element in the process of decarbonising the energy sector. The vision of implementing Offshore Energy Hubs in the context of exploiting offshore wind potentials in Northern Europe is led by industry and has quickly taken up a spot in the political discussion on national and European level. This research develops a survey scheme inspired by multi-criteria analysis to assess the main drivers in the development of Offshore Energy Hubs. We propose a definition, present the scheme, and conduct a survey based on the scheme for the case of the North Sea offshore energy infrastructure. Applying the suggested survey method to the context of the North Sea, we identify five trade-offs to be considered. The significance of the environmental benefits is strongly linked to the choice of materials and designs; changes to current assumptions may flip the system's benefits and turn the project into a series of sunk investments; coordinated and integrated planning is key to boosting the project's efficiency; offshore energy infrastructure presents a technological solution to energy system decarbonisation and needs to touch base with societal desires and behavioural solutions; and Offshore Energy Hubs are currently standalone solutions with no competitors, which makes their benefits impossible to compare.

1. Introduction

Offshore energy hubs (OEHs) – in the Danish context often referred to as *energy islands* – are being handled as a key component for the European Union's pursuit of decarbonisation targets. OEHs have so far not been a major part of research into future renewable-based energy systems. The idea originated in the European context of energy system transformation, and most examples and studies have involved European issues. However, the concept is widely applicable in any context of combining offshore and onshore energy systems at a large scale.

The vision of OEHs involves the development of large-scale assets in the sea that will allow the collection of wind energy and energy conversion and storage [1]. Embedded in offshore grid infrastructures, OEHs aim to contribute to the decarbonisation of the energy sector. The term generally refers to a combination of a large number of recent developments and system configurations moved into a new context. The main challenge in the development of these hubs is to identify the components individually and to then translate this knowledge about these components from the original context to their application to OEHs. Research into OEHs will come across as for example multi-energy systems, energy hubs, integrated energy systems, smart energy systems, energy system integration, and sector coupling, and more technological elements such as high-voltage direct current systems, offshore grids, energy conversion technologies, and energy storage.

This research develops a survey scheme inspired by multi-criteria analysis to assess the main drivers in the development of OEHs. We propose a definition of OEHs, present the assessment scheme, and conduct a survey based on the scheme for the case of the North Sea offshore energy infrastructure. The contributions of this paper are threefold:

1. It suggests a definition of offshore energy hubs and describes the main concept.
2. It develops and provides a generic assessment scheme based on technical, economic, ecological and societal criteria to survey the value of OEHs. This can serve as a basis for further scientific methods to be developed and support stakeholders in their assessment process of OEHs.
3. It applies the developed scheme to the case of the North Sea to identify the key drivers of OEH infrastructure and to point out strategic trade-offs relevant for European and international progress.

Abbreviations: GW, gigawatts; MCA, multi-criteria analysis; NSWPH, North Sea wind power hub; OEH, offshore energy hub; TSO, transmission system operator

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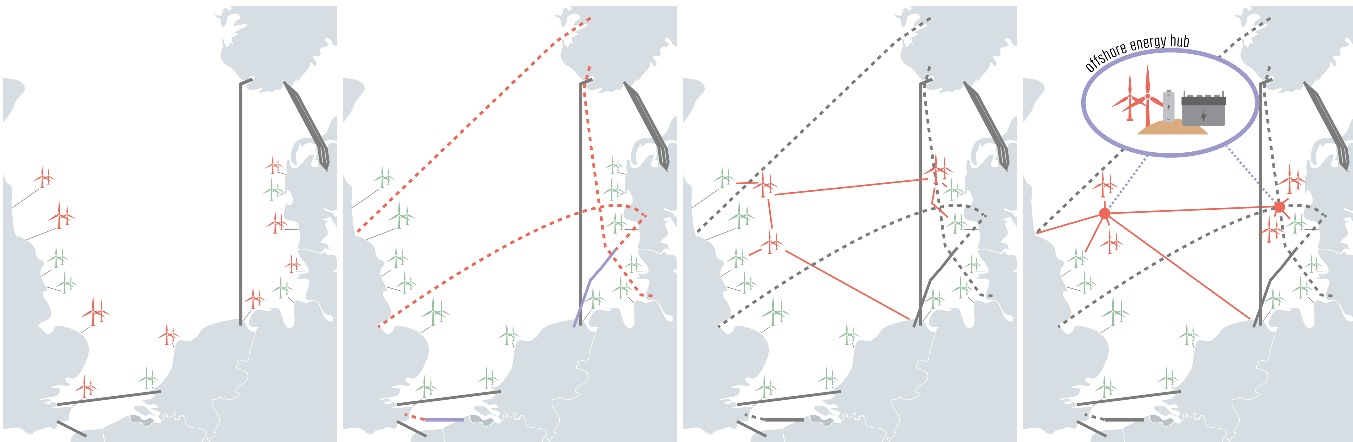

(a) Offshore wind is rolled out along the coasts.

(b) Additional interconnection via sub-sea cables (purple and red).

(c) An offshore grid develops to integrate offshore wind and interconnection.

(d) OEHs emerge at offshore grid nodes and may establish conversion and storage technology.

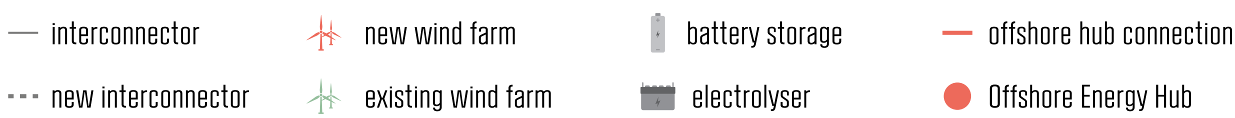

Fig. 1. The energy strategies for offshore regions have undergone the stages depicted in Figure (a)–(b). Starting with the emergence of connected offshore wind farms, Figure (a), the subsequent interconnection via sub-sea cables enabled further integration, Figure (b). Future plans include the construction of an offshore grid, Figure (c). As an additional component within this offshore grid vision, OEHs are suggested to emerge as elements offshore with storage and conversion units close to wind farms, Figure (d).
Source: Authors' illustration, partially based on ENTSO-E [2].

The definition is based on descriptions in scientific literature and project reports. The assessment scheme broadly follows the approach of multi-criteria analysis but leaves out quantitative work to focus on the structure and criteria assessment only. Applying the scheme to the North Sea projects, we find a fair body of literature and several large research gaps. One main finding is that the concept of OEHs is built on immature offshore technologies, lacks scientific support for constructing the hubs, and involves high technological and financial risk. On the other hand, we observe that offshore connections that serve as interconnectors, in particular, can provide value and integrate electricity systems and markets, leading to improved welfare.

The remainder of the paper is structured as follows: Section 2 summarises the history of OEHs and presents a clear definition of them. Section 3 describes an assessment scheme along technical, economic, ecological, and social dimensions. We then apply the scheme to survey the first planned islands in the North and Baltic Seas in Section 4. We describe the main trade-offs that we can identify in Section 5. Section 6 summarises the value of the scheme and the key lessons.

2. Conceptualising offshore energy hubs

Offshore energy hubs developed out of a combination of several recent movements, largely originating in European discussions. The discussion started when offshore wind became a key element in the decarbonisation of energy production. The first offshore wind park, *Vindeby*, was built in 1991 in the Baltic Sea and operated by the Danish company Ørsted [3,4]. The capacity of offshore wind has been increasing ever since, especially in Europe. More renewable energy in a system goes hand in hand with the need for more flexible resources. Using the example of the European geographic area, we can describe how OEHs evolved and how they can be defined.

Traditionally, wind farms are connected by cable to their owner's market zones as shown in Fig. 1(a) while interconnection of countries' electricity system has been constantly expanding and is doing so still. Interconnection, as shown in Fig. 1(b), both allows countries to benefit from cheaper resources in other countries and creates system stability. The first sea connection was built in 1961, between France and the U.K., based on high-voltage direct-current technology, and its successor is still in operation. In 2015, a goal was set of 10% electricity interconnection in Europe by 2020 [5], targeting not only continental connections but also sea cables.

For offshore wind parks and interconnectors in Europe, the North and Baltic Seas quickly came into focus. Discussions of how to connect these wind farms to shore gained importance [6]. On the basis of the expansion of offshore wind in the North Sea and Baltic Sea, projects such as PROMOTioN, Baltic InteGrid, and NorthSeaGrid are suggesting new approaches to the connection of generation to the existing grids. One leading approach discusses to abandon the traditional wind farm-to-owner-country (home country) and country-to-country (radial) connections by building an offshore grid in an integrated or meshed structure [7,8] as visualised in Fig. 1(c). Radial connections, linking one country to another, are called interconnectors in Europe. In home-country modes, the wind farm is connected only to the country of its owner. In addition to simple connections to multiple countries and offshore wind installations, offshore grids can support the efficient use of offshore renewable resources [9] and lead to higher interconnection, which supports fully renewable systems [10,11]. This provides two main benefits: interconnection of countries and thus markets, and large-scale integration of offshore energy technologies [12]. The literature on modelling offshore grids is already improving, and a review by Gorenstein Dedecca and Hakvoort [12] sets up a framework for assessing the different studies.

In light of discussions about building offshore grids instead of radial connections to improve system efficiency [9,13], OEHs can naturally evolve at locations where the grid connects large generation to several surrounding countries and thus serve as power link islands [14] or hubs [15], see also Fig. 1(d). In general, an energy hub is an entity where energy conversion, storage, and conditioning take place [16]. The first vision of an offshore version of this ends the timeline in Fig. 1 with an unknown time horizon to this date.

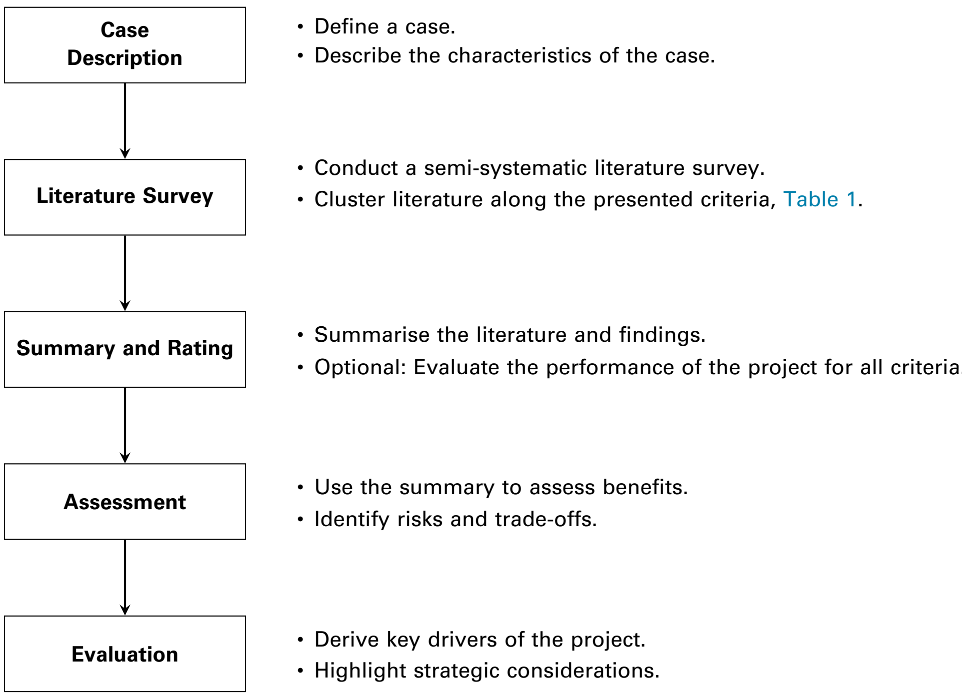

Fig. 2. Suggested workflow for a survey and assessment of offshore renewable energy projects. This study follows the workflow to assess OEHs.

Although the idea of OEHs originated in discussions around the North and Baltic Seas, the underlying concept can be seen as a generic approach to creating flexibility around power links and generation centres both offshore and onshore. In broad terms, we suggest that an OEH can be defined as follows:

> *An offshore energy hub is a fully renewable energy resource-based combination of assets that link at least two services, such as electricity generation, interconnection, and offshore storage. These services are relevant to energy system development and operation and foster decarbonisation of the energy sector while preserving the environment.*

Onshore energy and offshore energy hubs are both spaces where different energy carriers (wind, sun) are converted and stored, for example in the form of hydrogen or in batteries. In addition, different infrastructures are linked on a hub, most likely electricity with gas or heat. The main difference is the lack of direct conventional and residential load.

Projects that combine generation and interconnection are often referred to as *hybrid projects*, not to be confused with *hybrid assets*, which are infrastructure elements with the purpose of transmission and interconnection [17]. Examples of hybrid projects with hybrid assets are Kriegers Flak in the Baltic Sea and the Cobra Cable in the North Sea [18]. Following this definition, OEHs can be categorised as hybrid projects, under specific market designs also be seen as hybrid assets.

3. Assessment scheme for offshore energy hubs

OEHs are still a theoretical concept based on a vision. Many details have not yet been fully explored, for example size, location, and technology. Since European consortia presented the first ideas in 2016 [19], researchers have contributed studies of renewable offshore energy systems and their impact on markets, welfare, prices, system stability, marine ecosystems, and decarbonisation. To cluster and survey these studies around the concept of OEHs, we develop a review and assessment scheme inspired by multi-criteria analysis (MCA) and tailored towards organising and analysing literature on offshore energy infrastructure projects. The structured material can then inform an assessment. In the following sections, we describe the generic scheme, including a suggested workflow and the criteria for the review of OEH projects. In Section 4.4, this scheme is applied to the case of the European process which starts off with a definition of the respective case-specific details and key terms.

3.1. The scheme

In general, multi-criteria analysis sets a hypothesis and evaluates a project on the basis of several criteria [20]. The relevance of MCA for renewable energy projects has been recognised and summarised by Wang et al. [21], who list many examples of such applications. Munda [22] describes a significant driver of sustainability projects as non-monetary influences on the value of projects; that is, impacts that are hard to monetise such as intrusion, acceptance, and participation. Relevant assessment criteria are reviewed by Ilbahar et al. [23], and we use three studies to identify common criteria: Wang et al. [21], Ilbahar et al. [23] and Wilkens [20]. We use the core of the criteria from the literature and extend them with drivers that are specifically relevant to offshore energy infrastructure. This results in an evaluation that follows a qualitative approach on an ordinal scale for each criterion. As core part of this study, we suggest the workflow following Fig. 2 to asses OEHs.

As depicted, the assessment starts with a definition of the case to be analysed. The second step is a semi-systematic literature survey to identify studies based on selected search strings. The various assessment criteria are presented in Section 3.2. Based on these assessment criteria, the findings can be summarised, and the overall outcome for each criterion can also be rated. Then the benefits, risks, and trade-offs are identified. Finally, all these steps provide input to derive the key drivers and strategic challenges of the case. Section 3.2 explains the criteria used to cluster and analyse the literature and the summary (steps two and three).

3.2. Criteria

The criteria for the MCA suggested in this paper originate from a review of relevant assessment criteria by Ilbahar et al. [23], Wang et al. [21], and Wilkens [20]. We cluster these criteria from the literature

Table 1
Assessment Criteria for a survey of OEHs adapted from [23] and clustered into four categories including the three dimensions of sustainability (economic, ecological, and societal).

Technical	Economic	Ecological	Societal
Efficiency	Capital cost	Biodiversity & intrusion	Acceptability
Maturity	Governance & regulation	Climate protection	Health
Operations & maintenance	Market design	Emission (reduction)	Job creation
Safety & reliability	Ownership & operation	Land use & spatial planning	Participation
	Risk & uncertainty	Resource utilisation	Social benefits & equity

for the survey of OEHs into four groups: technology and the main sustainability dimensions, i.e., economy, ecology, and society. Table 1 presents the relevant criteria, and the following paragraphs provide further detail about the relevance and link of those criteria for the assessment of OEHs.

We recommend four **technological criteria** for assessment that are likely to heavily influence the performance of OEHs. Energy projects are very technical in character and require a strong assessment of the chosen technology. This assessment can be made from system and component points of view, which lead to different insights and highlights. In line with the literature, we find that technological *maturity* can reduce the risks of a project and is thus an important factor. *Technical efficiency* drives the competitiveness and economics of the technology and must be included in any evaluation of options. Further, *safety and reliability* are relevant characteristics of the technological performance to ensure long-term stability. Last, we consider *operations and maintenance* to be key for the success: the less cost and effort, the better.

Energy projects are capital intensive and of high economic importance in today's energy dependent economies. We formulate five **economic criteria** that are relevant to assessing OEHs and their economic performance. *Capital costs* are a key value that guiding cost-benefit analyses use as input, and they thus are a criterion. When projects are operational, their economic performance depends on markets, rules, and business models. To reflect the readiness of the economic frameworks for OEH projects, we include *governance and regulation*, which provides the framework for operation and leads the way to successful implementation. One part of this is *market design*, which we include as a separate criterion in our analysis to reflect the market's readiness to absorb new models and setups. In addition, we regard business setup and *ownership and operation* as highly influential in this cluster due to the allocation of costs and benefits. Last, it is relevant to assess *economic risk and uncertainty* for extracting how vulnerable projects are, as investors seek to minimise risk and uncertainties.

Decarbonisation of the economy drives the transformation of the energy system and induces the expansion of offshore energy sources. Yet *emission reduction* and *climate protection* are not the only ecological criteria to consider when looking at the value of OEHs. Besides the non-negligible factors of emission reduction and climate protection, we present three more **ecological criteria**. Offshore energy project are resource intensive, use space, and intrude on untouched marine space. We stick to the most common criteria from Ilbahar et al. [23] and add *biodiversity and intrusion*, *land use and spatial planning*, and *resource utilisation* to the above. These last three criteria cover the role of competition for space that is to be shared between nature and humans, and which must be maintained to ensure functioning ecosystems.

Last, we have five **societal criteria** to highlight the role of society as a driver or delayer of these projects. As a society, we depend heavily on energy and thrive by keeping that dependence while reducing carbon emissions to mitigate climate change. However, the transformation of this energy economy to clean sources faces significant other obstacles and has impacts in many more domains than just the technical, economic, and ecological. Besides immediate and measurable impacts like *job creation* and *social benefits and equity*, which develop alongside a transition and projects within it, there are less quantifiable indicators. Among those, we assess the effects of the projects on *health*, following the debate about climate change threatening our habitat. In addition, we value *participation* in the projects and add a factor of *acceptability* as part of this assessment.

4. Assessing sustainability: Survey of European progress

We apply the scheme described in Section 3 to the case of the North Sea OEHs to derive generalised learning. Following the workflow, we describe our case in Section 4.1. Section 4.2 presents the literature survey, including all the criteria. In Section 4.3, we summarise the literature and present an evaluation using an ordinal scale. On the basis of the summary, we describe benefits, risks, and trade-offs in Section 4.4 and derive strategic challenges in Section 5.

4.1. The case of the north sea

Europe is currently the world's leader in offshore wind: Offshore wind potentials in Europe are high in the North Sea region and thus involve many adjacent countries, such as Belgium, Germany, Denmark, the Netherlands, France, Norway, Sweden and the U.K. [24]. The North Sea region is not the only part in Europe to develop offshore wind power, but together with the Baltic Sea it is the frontrunner. With its offshore renewable strategy [6], the European Commission formulated a clear direction for a system transformation based strongly on offshore energy systems.

The Danish government announced two *energy islands* as part of its plan for energy and industry to reach 70% reduction of CO_2 emissions by 2030 [25]. This term should not be confused with islanded solutions onshore, where areas have their own energy supplies and are disconnected from the main electricity network, or with physical islands that aim to have fully renewable energy systems or have reached full decarbonisation, e.g. Samsø Energy Island or Madeira. The Danish transmission system operator (TSO) Energinet has also set up the *North Sea Wind Power Hub (NSWPH)* consortium with the German and Dutch TSO TenneT to promote an OEH in the North Sea within the *Trans-European Networks for Energy* priority corridor. This priority corridor allows for EU funding of projects of common interest [26]. Although the NSWPH is still seeking approval at the European level, the Danish government passed an agreement on details about the first island in Danish waters: 210 billion DKK, an artificial island, 3 GW offshore wind, and interconnection capacities to surrounding countries, to be in the full package operational by 2030 [27]. This quickly developed into the current target of two Danish islands: one in the North Sea and one in the Baltic with 10 GW and 3 GW of wind energy connected, respectively [28]; see Fig. 3.

The Danish projects and the NSWPH are the three leading OEH projects, but the concept is also relevant to Norwegian offshore energy [30], Belgium and Germany. All the published visions and concepts follow the generic approach described in Section 2 and consider placing conversion and storage technology close to offshore wind. Analyses to assess the value, determine the design, help with policymaking and ensure acceptance have not been conducted for the case of the North Sea.

4.2. Survey

Sections 4.2.1–4.2.4 provide the results of the literature survey. We follow a semi-systematic literature review [31] which considers a literature search on Scopus and Web of Science using the search strings *offshore energy hub*, *offshore grids*, *energy islands*, and *offshore sector coupling*. We obtain a total of 479 articles combined from both databases.

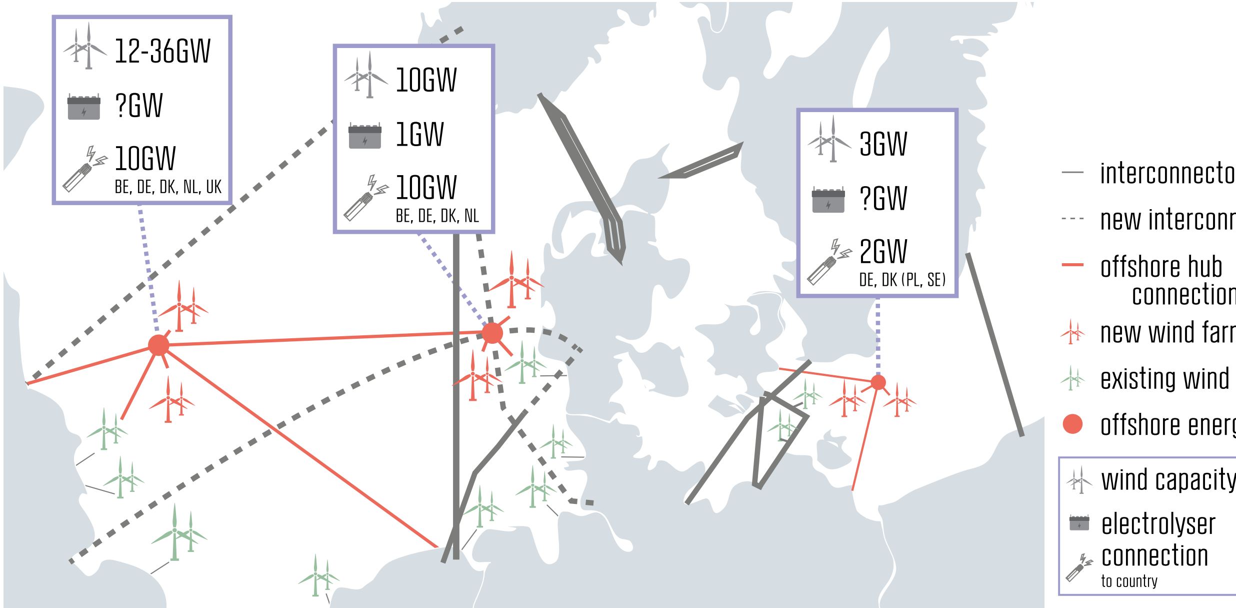

Fig. 3. Overview of current OEH projects in Northern Europe.
Source: Author's illustration based on COWI [29] and North Sea Wind Power Hub [1].

This consists of the following results for the keywords (Web of Science/Scopus): offshore energy hub (5/12), offshore grid (160/295), energy island (66/169), and offshore sector coupling (8/41). We then disregard literature on decarbonising physical islands, offshore oil and gas production, and pure physics research on electrical systems. This reduces the number of articles that we consider for the survey by 80% since most research is dealing with technical HVDC research or microgrids on existing islands. Wherever we see a lack in the literature after sorting or are able to identify related topics (for example, market design for offshore wind, job creation in the renewables industry), we manually search for references on these topics and preferably use reviews as references. The following sections present the literature that is relevant to assessment and evaluation. We structure the obtained literature along the criteria presented in Table 1.

4.2.1. Technological criteria

The technological dimensions of an OEH include all the technologies the hub is home to or that are connected or related to it. In some locations, it might be more suitable to create a large wind power hub, while others invite solar power, conversion (for example to green fuels), and storage technologies as well. In designing an OEH, the technical dimensions must include the technical devices installed at and around the OEH, their components and the means of connection and operation of those, and the system aspects. From a technological point of view, plans for sizing, mode of connection, and operation can depart from the conventions on energy hubs, virtual power plants, and multi-energy systems to determine an efficient path.

An OEH is placed offshore and must be connected to the land. As nodes in a meshed offshore grid would invite OEHs to evolve, there is a technical overlap between the design of offshore grids and hubs [13] creating synergies. Although there seems to be a clear consensus that OEHs are the point to harvest offshore wind energy to send it bundled into an offshore grid, there is no straightforward plan for what technology should be installed in addition to this. North Sea Wind Power Hub [1] envisions an OEH that is home to electrolysers that produce hydrogen; Siemens, Ørsted and ITM develop technology to produce hydrogen inside wind turbines, which would turn each hub into not only a power link but a hydrogen link island [32]. Batteries, pump storage, and gas tanks can also provide flexibility, though their shape, size, and combination have not yet been investigated and have never been tested offshore. [33] argue that green fuel production offshore is technologically feasible. The first results point to electricity-only production being the most valuable element to invest in, but combined operation can also be valuable and feasible [34]. We evaluate the technical characteristics along the defined criteria in the following in more detail.

Efficiency. Conversion technology in the form of power-to-x transforms electricity into a different energy carrier such as hydrogen, heat, fuel, or other green gases [35,36]. Whenever electricity is converted, losses occur, and there is a different target market with other characteristics and a design that affects the costs, benefits, and long-term profitability of the installed technology. With the possibility of electrolysers producing hydrogen on OEHs (potentially even inside wind turbines), the economics of hydrogen production [37] will significantly influence size, operations, locations, and connection to gas and other network infrastructures. The first studies show a trade-off between direct electricity use via cable connections and hydrogen conversion [38]. Gea Bermúdez et al. [39] find that cables are preferred over hydrogen production if there is no specific hydrogen demand. Yet electrolysers can be a flexibly operated asset [40] for ancillary services, but may not serve as balancing component in intraday markets [41]. As for the type of technical connection high-voltage grid connections and low-inertia setups are suitable characteristics that can support OEHs where wind energy is harvested and collected at a central point [42]. Studies show that the implementation of high-voltage direct current power lines can support the efficient design and operation of offshore grids [43].

Maturity. Component-wise, offshore wind is a rather mature technology [44], but offshore electrolysis is still in its pilot phase [36,45,46]. Battery storage and other conversion processes have not yet been tested offshore, nor can they be related to any similar offshore constructions. Mere oil and gas platforms are similar in their foundations to one of the options suggested in COWI [29], however. Those platforms are well tested around the world and are more explored than sand constructions.

Operations and maintenance. Many needed add-ons to offshore wind technology do not yet exist as commercial hardware. Although energy generation potential is much stabler and higher offshore, there are disadvantages as well: high costs of engineering, installation, and maintenance, a need for grid expansion, and limited access [4].

Safety and reliability. Early research indicates that a meshed grid structure in the sea can stabilise renewable-based systems, but there is not yet enough evidence to achieve additional flexibility through the creation of technology-combining offshore hubs as Fig. 1(d) suggests in the purple bubble. The value of shifting those hubs to other highly interconnected areas, such as onshore landing points, must be gauged before support is granted, similar to what Singlitico et al. [47] suggest. OEHs in operation are expected to support the decarbonisation of the energy sector and create a reliable and resilient infrastructure for operating a fully renewable system. The technology at the hub must be chosen with respect to technical interaction and operation to keep costs and maintenance needs low while still extracting the most value from the new investment. If wind power alone is not considered definitive of OEHs, insights from research into sector coupling and system integration can help us determine the specific characteristics of other power generation, storage, and conversion technologies [40,48].

4.2.2. Economic criteria

The most efficient technical composition is not always the most economical. The reasons can be manifold, including lack of policy support, cost of technology, market rules, and varying demand or supply. To combine the technical and economic dimensions for an overall efficient outcome, different trade-offs must be weighed and policy and technology aligned. Although the technical dimension will decide the choice of technology, the economic framework must ensure profitability and will need to guide implementation.

Capital costs. In the specific case of OEHs, the combined strengths of hubs and integrated offshore networks let them outcompete radial and home-country connections [49]. Coordinated planning puts pressure on the profitability of large infrastructure investments in offshore grids: meshed grids lead to lower system costs but depend heavily on coordinated planning and building efforts [50–52]. So far, the development of offshore wind, grids, and interconnection has remained a national task [12]. In an international setup, difficulties arise among partners, and the task is to develop along national or regional plans [53]. Traber et al. [54] argue that the harmonisation and coordination of efforts at grid expansion and capacity building can have a positive long-term effect on costs in general and with respect to offshore infrastructure projects. The interconnection of strong markets with asymmetric renewable capacity is seen as stabilising prices in the connected markets [55]. The capital costs for offshore wind technology is foreseeable [56], but for other assets on the island (electrolysers and storage) and the island construction itself bears risk and capital costs are unknown which may imply high cost. Singlitico et al. [57] present an approach to determining offshore production costs for hydrogen and show that offshore placement can make the wind parks more economical through peak shaving production, and Gea Bermúdez et al. [39] argue that offshore hydrogen production will play a small role.

Market design. Besides coordinated planning and investment, market design is crucial to success. Market design for OEHs includes questions about the owner and operator of the technology, pricing rules, and regulatory frameworks. Due to the renewable energy generation around hubs, the market design must align with the requirements for a high-renewables scenario that unites intermittent resources with necessary levels of competition while either addressing or avoiding market failures [58,59]. OEHs are just another component of the renewable offshore setting and add a layer of complexity to it. In general, two market design options seem to have become the leading concepts: designs of home markets and offshore bidding zones have been suggested by Weichenhain et al. [49] and Nieuwenhout [60] on behalf of the European Commission. These designs have been taken up by the North Sea Wind Power Hub [17] and were commented on by Energinet et al. [61]. Using a system model, Kitzing and Garzón González [7] and Gea-Bermúdez et al. [62] evaluate the two designs for a Danish energy island with only wind energy connected and conclude in favour of the offshore bidding zone. Lüth et al. [41] add hydrogen production to the OEH and show that offshore bidding zones lead to more hydrogen production at slightly higher prices offshore while keeping onshore production prices stable. Durakovic et al. [63] add that offshore production, however, will increase electricity prices in some countries.

Governance and regulation. Offshore wind projects need grid access, and instead of farm-to-shore connections, a meshed infrastructure could support the integration of far-out offshore wind projects. The regulatory models for grid infrastructure to connect such farms differs around Europe and even around the Baltic Sea [64] and North Sea [65]. Whereas harmonisation towards a more competition-oriented model would enhance offshore wind projects, harmonisation towards a TSO-model that supports advanced connection planning would be more beneficial [65]. The key to the overall process is the alignment of rules [66]. Due to the variety of policies around Europe, Sunila et al. [64] suggest the creation of a supra-national TSO for a pure offshore grid: a single operator of an offshore grid as a fully European solution under EU regulations, rather than coordinated and cooperative approaches. It further remains relevant how offshore hydrogen infrastructure will be regulated and if regulation will consider joint investments into production and transport assets for initial upscaling processes

Ownership and operation. Current literature focuses on economic regulation and market design for offshore wind, offshore grids, and OEHs with solely wind energy connected. An OEH might include further technologies such as batteries, pump storage, or electrolysers. For now, there is evidence supporting offshore grids and wind power islands being valuable to the system, which highlights the need to allow for their emergence through market design and economic regulation. Kitzing and Garzón González [7], among others, provide first indications to how this can be done. Sunila et al. [64] and Meeus [65] present ideas for addressing the difficulties about the ownership and operation of the offshore grid. In the presence of conversion technologies such as electrolysers, the economics of renewable energy conversion [37] will be a key driver. The produced and available quantity of hydrogen affects the path to integration with the gas sector, which will add a market- and system-integration component to the energy island. This will open a discussion about several modes of operation and ownership structures surrounding power-to-x, which is already heavily discussed for onshore technologies [67].

Risk and uncertainty. If technical analysis shows value added by storage or electrolysers on OEHs, the economic framework will need to catch up with this recommendation and investigate whether support schemes are needed to extract this value. Financing schemes for offshore wind energy have shown that the support scheme influences the deployment of the technology and must be adjusted to the rolled-out capacity [68]. Yet the whole concept of OEHs is new and carries uncertainty in many variables.

4.2.3. Ecological criteria

OEHs are being developed to help decarbonise the energy sector, and it seems like an obvious assumption that the projects will support green transition. To verify this, we summarise existing studies on the environmental and ecological impacts of OEHs. Each OEH will be different and thus have a different impact.

Resource utilisation. The first studies evaluate various foundations, such as the construction of sand islands, caisson islands, or a platform [69]. COWI [29] evaluated the impact of each foundation type on behalf of the Danish Energy Agency and found that sand island solutions (sænkekasseø) have the highest additional carbon footprint due to material production. An analysis of repurposing existing offshore infrastructure has not been conducted.

Emission reduction and climate protection. Effects of construction might counteract the environmental benefits of an energy island. The concrete industry has the largest industry emissions in Denmark [70], and scarcity of sand must also be considered for large new constructions [71,72]. Cables as a connecting infrastructure emit electromagnetic waves, and phases of construction can disturb natural processes in the sea.

Land use and spatial planning. Onshore wind installations quickly led to public opposition, and offshore wind farms were thought to resolve problems of visual and environmental impact, planning, and spatial considerations [73]. The same considerations will be necessary with respect to OEHs. The more technology is added to the hub, the more we will need to move these industrial centres away from the shore. But though this might resolve public acceptance problems, there are trade-offs in space, ecosystems, biodiversity, health implications, and the use of resources. The sea seems to provide large space and unlimited possibilities, but sea area is limited, and marine spatial planning is important when increasing offshore activities: shipping, energy transport and generation, tunnel and bridge building, fishing and farming, and maintenance of natural recreation areas and ecosystems. With OEHs, we add capacity for energy transport, generation, and storage. Well-designed incentives from policymakers are needed to prevent congestion but use the available space for infrastructure efficiently.

Biodiversity and intrusion. Species under the sea and in the air are affected by the building of offshore wind generation [74,75]. The phase of construction threatens the submarine wildlife, such as fish and molluscs, the most. Once construction is completed, new ecosystems can evolve, and they have done so in the North Sea [76]. However, the long-term effects remain unknown. Frequent interventions in the sea can destroy newly developed ecosystems, another point of consideration in the construction of energy islands and the choice of size.

4.2.4. Societal criteria

In the long term, society will profit from investments in clean energy technology. An energy-driven lifestyle can help societies develop while preserving air quality and lowering environmental pressures. Whether investments in OEHs will benefit society as a whole depends on all the aforementioned criteria: technical and economic design and consideration of environmental impacts.

Acceptability. Offshore wind parks developed fast when land for onshore wind became scarce [77] and public opposition to onshore wind farms increased [73]. The more stable winds and greater space justified the expansion of offshore installations. Public acceptance is said to increase with participation [78], which in the case of OEHs will not take place. The costs of acceptance are high, and in some cases outweigh the high investment costs [79].

Health. There is a wide consensus that cleaner air is beneficial to health [80,81]. Energy production and industry-related CO_2 emissions reached a global high of 36.3 gigatonnes in 2021, with coal in the lead [82]. These record emissions contribute about 40% of global greenhouse gas emissions and thus add significantly to air pollution. The adoption of clean technology will have health benefits for the population and reduce health system pressure and costs.

Participation. OEHs have met high acceptance rates so far, but acceptance is not triggered by participation, as in other top-down approaches. Local and decentralised concepts often encourage acceptance through participation [83–85]. Centralised, large-scale projects such as OEHs and large offshore wind farms, centralised power-to-x plants, and big storage units do not involve citizens but require infrastructure development, which may affect acceptability if not done inclusive [86].

Social benefits and job creation. Under current designs, the costs and benefits of these integrated solutions will be distributed unevenly unless policy implements reallocation mechanisms [87–89]. The allocation of costs and benefits among the ideally involved parties influences willingness to participate. In the absence of re-allocation mechanisms parties may withdraw and bring significant disadvantages to the overall venture. Job creation in the renewable energy sector was seen early on as an economic opportunity [90–92], and it is needed to compensate for job losses in the sectors that are replaced [93].

4.3. Summary and rating

The first studies of OEHs aim to answer to emerging questions about the concept. The details of the criteria defined in Section 3 present a first glance at the obstacles to developing OEHs in the North Sea. To summarise the main obstacles in the different categories, we evaluate them and present the results in Table 2. In the Table, Column 2 indicates the performance of the concept in our assessment. In the assessment, we distinguish five levels: poor (−−), weak (−), fair (∘), good (+), and excellent (+ +). This qualitative assessment is done on an ordinal scale and there are two evaluation factors: (i) a clear statement in the literature that relates to the respective rating, or (ii) an indication or learning from related topics that is clearly applicable to OEHs. Column 3 explains and supports our assessment, and the references for this are collected in Column 4. In the following text, we elaborate on the overall findings that are summarised in Table 2.

For the technological assessment, we conclude that the North Sea OEHs can benefit from efficient wind energy conditions offshore and fairly mature offshore wind technology. Interconnection allows for stabilisation of the broader European electricity system, but experience with interconnected wind farms is limited and the system stability impact is not large, so we rate it at fair quality but not excellent. Sector integration is one of the main work items at the moment and suffers from immaturity despite great working examples. Offshore electrolysis is not operational at all, and the immature technology poses a high risk and relies on heavy effort for operations and maintenance work. Overall, the maturity and efficiency of offshore wind energy invite to proceed with the project. First experiences with system stability through increased interconnection have provided good prospects. Immature offshore technology, increased maintenance effort, and lack of sector coupling success are currently the weak points of the projects.

As for the economic parts of the projects, most are not yet defined or adjusted to facilitate system and market integration. Governance and regulation in Europe are focused on onshore national solutions, but for OEHs they will need to extend their scope to multinational solutions and legal frameworks. We therefore cannot finally evaluate the performance of OEHs with respect to governance, ownership, operation, and market design, and we highlight the fact that changes and future frameworks for offshore energy projects will influence the success of OEHs. The lack of guiding European regulations is one source of risk and uncertainty. High capital costs, immature technology, and lack of experience are others where the projects rate as poor.

The ecological assessment has a two-part result. The use of offshore wind as a resource leads to emission reduction and faces less competition in offshore areas, and we will need less space and technology offshore due to higher capacity factors. However, OEHs with added hub components have undefined benefits. Construction of the island itself creates additional carbon emissions, and construction and decommissioning destroy and intrude new areas. In addition, the construction of an OEH requires resources, and if existing offshore constructions from oil and gas extraction in the North Sea cannot be repurposed, additional emissions will be created.

Society benefits largely from reduced emissions improving health, and the transition to renewable energy creates many jobs along coasts and at harbours in the North Sea region. The long-term effects on society and equity cannot be evaluated yet, but early insights propose

Table 2
Summary and rating of the OEH project idea and concept. This is based on a qualitative evaluation that either is reference-based or reference-informed.

Criteria		Note	Related literature
Technological			
Safety & reliability	∘	Evolve where there is large wind potential and connection to offshore grids: can also stabilise the offshore grid.	[42,43]
Maturity			
Offshore wind	+	Semi-mature technology, international learning effects	[44,56,77,94]
Offshore electrolysis	−−	No experience, onshore counterparts are also still under development.	[36,45,46,57]
Sector integration	−	Gaining experience onshore, offshore setting is largely immature/unexplored.	[33,34,38,95,96]
Interconnection	∘	The first hybrid project started in 2021, interconnectors are not fully exploited yet.	[9–11,97]
Efficiency			
Wind energy	+	Offshore wind locations provide better wind conditions.	[4,98]
Electrolysis	−	High conversion losses and potential low capacity factors if not dedicated to hydrogen production.	[35,36,40,48]
Operations & maintenance	−	Higher efforts and costs offshore, centralised setup for better access.	[4,94]
Economic			
Capital cost	−−	High cost, unexplored concept, high dependence on interest rates, sustainability influenced by choice of financing source (green finance).	[33,37,53,54,68,99,100]
Ownership & operation	∘	Currently undefined structures. Promising suggestions available in the literature.	[47,64,67]
Governance & regulation	∘	Uncertain legal definition of OEHs. Future frameworks will shape the performance. Some solutions show fair possibilities.	[64,65,101]
Market design	∘	Not developed, bidding zone configuration influences prices significantly.	[7,49,55,58,59]
Risk & uncertainty	−−	High risk and uncertainty due to interest rates, immature concept, international collaboration, geopolitics.	[102–105]
Ecological			
Emissions (reduction)			
Offshore wind	+	Key resource for energy transition.	
Energy island	−	Undefined climate benefit, construction emissions high.	[29,106]
Land use/spatial planning	+	Use of untouched space, trade-off between repurposing and new construction not considered.	[75,98]
Resource utilisation	−	Intense sand use, large land fill.	[27,29,71,72]
Climate protection	−	Additional benefit of artificial hub not visible.	
Biodiversity & intrusion	−	Seen as an intrusion into new areas; animals and plants can adapt and benefit, but construction and decommissioning causes destruction.	[74,76]
Societal			
Acceptability	++	Increased acceptability due to avoiding close interaction with humans.	[73,77–79]
Social benefits & equity	∘	Lighthouse project will receive public funding, risk for costs exceeding benefits, first insights propose welfare increase.	[87,88,88]
Health	∘	Renewable energy improves air quality; long-term environmental consequences on whole biosphere unexplored.	[80,81]
Participation	−−	No immediate participation planned and no discussion of allocating benefits.	[78,86]
Job creation	+	Northern Europe maintains and expands renewable energy industry.	[90,91,93]

−− poor, − weak, ∘ fair, + good, ++ excellent.

that welfare will increase. A public project is a risk that society might need to pay for if it fails. The acceptability of OEHs can be rated as sufficiently high because of their distance from humans. General participation in OEHs is low, and this presents a downside.

Overall, for each category we can identify benefits and weaknesses. We use the assessment to derive opportunities, risks, and barriers in the following sections.

4.4. Assessment

OEHs open for **opportunities** for market integration across countries and for enhancing the interconnection of the involved parties to construct the island. Interconnection has been shown to stabilise the energy systems and belongs to the priority corridors for the electricity grid [107]. The bundling of offshore resources with the development of grid infrastructure can allow the harvesting of large unexploited offshore resources while being less space-intense. OEHs also allow for a more cost efficient way of connection to shore: combined and bundled cables from central offshore locations provide an advantage over many parallel small connections. If OEHs include energy storage and power-to-x, possibilities for energy system integration and emerging synergies can be exploited. High acceptance rates and job creation further support the North Sea project.

We can also identify **barriers** to OEH projects. Those can be overcome with policy instruments, advances in research and development, and education and participation. The first step, of identifying the ideal location for an OEH, is one barrier. The topic is highly political [102], and there is a risk of strong disagreement or opposition. In the current situation, there is a front runner (the North Sea region) and bottom-up development (industry-led) in a system with mostly top-down regulation, similar to the case of offshore grids [108]. In recent years, geopolitical tensions have also influenced reliable energy supplies and lead to threats and sabotage, for example, with incidents by the Nord-Stream pipelines [109] and the Baltic connection between Finland and Estonia [110]. In addition to geopolitics and interference with national plans, there is a lack of clear guiding research on this topic. The first studies have emerged discussing offshore grids and market design, but the smart approach to OEHs has not been explored. Policymakers rely on information and education by researchers to create sustainable and valuable frameworks for the development of such projects. In the absence of studies, progress will be slowed by lack of information.

Just as for offshore grids, the optimal design of OEHs within an integrated grid structure might not be reachable in the desired shape: integrated and coordinated planning over a long time horizon brings **risks** and uncertainty, and it is not addressed by any regulation such as *Trans-European Networks for Energy* [111]. An integrated system design including well-connected OEHs can have significant benefits. But to reach this ideal scenario, the planning and building must be integrated to ensure that gradual development of large-scale infrastructure is well coordinated, and the optimal layout can be reached by passing several milestones. Radial connections might still need to be part of the system [111]. Other risks involve financing strategies, influences of interest rates and on immature electrolysis and offshore technology, and uncertainty about the acceptability of supporting such large infrastructure projects. To improve project outcomes, modular design can help mitigate risk and ensure that each module can still exist if the whole does not materialise.

5. Research gaps and strategic considerations for offshore energy hubs

In planning OEHs, we can use this analysis to identify key drivers and strategic considerations. Although the time frame for the Danish lighthouse OEH is set, the joint international project for the North Sea is still pending, and Belgian, German and Norwegian projects are developing, too. Research into a generic design as well as the specific design of the Danish OEH is still scarce, but future projects will be able to make use of the lessons of the first project in Danish waters. In general, there are still challenges to be faced in the case of the North Sea as well as for other hubs internationally. Research might provide answers quickly, but at this point we draw qualitative conclusions from this analysis, with five main strategic considerations to be answered for such projects—relevant for the North Sea and internationally. These are derived from trade-offs that we identified following the assessment scheme.

1. ***Significance of environmental benefits***
Although the vision of OEHs is in line with the decarbonisation of the energy sector to mitigate climate change, it remains unclear how much they will contribute to the targets of reducing emissions over their lifetime. One critical element is the construction phase: The building sector produced 11% of global emissions in 2019 [112] and must follow a targeted decarbonisation strategy to make the hub more beneficial than an onshore setup without the need for extensive foundation building, steel, or concrete [71]. It has not been determined whether OEHs will have a positive impact through the creation of a circular economy [113] or if emissions reduction is low as outlined in Advisory [106]. The choice of foundation, size, and modular character may significantly influence the significance of emission reduction through energy islands as calculated by COWI [29].
2. ***System benefits vs. sunk investments***
Once OEHs are operational, they are expected to provide flexibility, cheap electricity, and grid services, and to stabilise a fully renewable energy system. The first calculations show that OEHs have significant benefits for energy systems in operations and decarbonisation [1,49]. However, if one or more of the current assumptions (e.g., degree of connection, scale of power connected, capacity of interconnection) does not hold, this picture will change. The impact of changing assumptions remains unclear, but the risk of sunk investments being borne by society is large. In addition, markets and governance will play crucial roles. Unless policy sets the right framework, market failures [58] could harm profitability.
3. ***Reliance on coordinated planning & geopolitics***
An OEH is to a large extent an add-on to the discussion of meshed grid infrastructure in the sea. The first research on meshed offshore grids has shown that such a project is highly sensitive to uncoordinated planning [52,111]. An OEH has common grounds with regulated system operators and players in the competitive market, i.e. electricity generators. In addition, the projects involve many countries in the beneficial cases of reaching high levels of interconnection. Economies of coordination will be a crucial factor to make investment, ownership and operation turn into a coherent system. Policymakers will need to assess the trade-off of unbundling versus economies of coordination carefully. However, geopolitical tensions need to be considered as risk for developing a highly international and connected system. Recent incidents involving sabotage in international waters (see, [109] and [110]) and higher numbers of cyberattacks represent an increasing threat.
4. ***Beyond technological solutions***
Technological change and adaptation have been the main focus lately in the discussion of mitigating climate change. Although many solutions are technical, the social and behavioural aspects of tackling decarbonisation are often overlooked. International Energy Agency [114] presents an outlook on CO_2 emission reduction in which end-use fuel switching and efficiency gains contribute a share of 43%, which includes end-users. The impact of a rebound effect is not consistently quantified, except for direct rebound being within a range of 0%–30% [115]. The rebound effect in energy clearly counteracts the full exploitation of efficiency gains and increases the need for additional energy. Strong policies in favour of energy saving and energy sufficiency [116] do not clearly support the current layout of the energy industry, but they can relieve society of expenses for the decarbonisation of the energy sector.
5. ***OEHs as the best or the only option?***
OEHs represent a clear vision. In the light of strong challenges and the long path to full decarbonisation, this vision gives a clear picture of a solution. Beyond the image of OEHs, the vision becomes blurry. The options for hitting the targets have not been compared extensively. Although the focus of OEH creation is bundling centralised generation and storage, other ideas aim at a solution aligned with the distributed and decentralised character of renewable energy generation: local and small solutions such as peer-to-peer electricity markets [84,117]. It is unclear whether these approaches are alternatives or complements. Small solutions at the end-user level or close to it can lead to greater acceptance due to larger involvement [118].

6. Conclusions and outlook

The vision of OEHs will move quickly towards implementation. It remains unclear what the first hub will look like and whether the concept will take off and expand outside Northern Europe or remain a one-time project. Investment costs are high, so societal benefits need to be large too.

This paper presents a scheme for assessing OEHs. It discusses aspects of the planning, structuring, and design processes and suggests a literature-based analysis of the relevant criteria using a multi-criteria analysis inspired structure. We find that OEHs combine mature technologies, such as offshore wind power, with immature technologies that pose a high risk. The economic frameworks are not yet settled and make final evaluations of the benefits impossible. Experience, however, does suggest that the economics of offshore projects drives their viability. The capital costs for large infrastructure projects (and the necessary research and development) are high and the payback is uncertain. The development of economic frameworks and regulations is the key to creating an efficient technical system: not only the cost of each item, but the regulatory framework and market design are decisive in creating a long-term, sustainable OEH. For the environment and society, the impact is scattered: the project might lead to cleaner energy supplies and better health and job situations, but it could damage wild waters in ways that are not measurable today. Although optimal technical and economic solutions seem feasible, the environmental aspects will determine the impact on the overall target of a socially acceptable, cheap, environmentally sustainable transition to a low-carbon society.

The survey of the literature on OEHs leads to conclude with five strategic considerations, including the trade-offs we must make in deciding to implement OEHs: The environmental benefits are unidentified, and there is no benchmark to measure alternatives against. The project is subject to high financial risk, and we cannot preclude sunk investments, especially due to reliance on coordinated planning and consideration of geopolitical matters. The ideas presented on OEHs suggest that technology will be the path to energy system transformation by letting us move projects out of areas with little public acceptance. This stands against other solutions, however, and no studies have compared systemic approaches, such as decentralised and behavioural solutions, to centralised technological ones. These considerations arise in part due to the lack of research and therefore of present research opportunities. That said, further research must address the characteristics and design features outlined here to further identify profitable and smart specifics. This could involve analysing the choice of technologies, the design and specifications of those technologies, and the operational modes. This survey lists a large number of questions and items to be researched, and Table 2 gives these insights in terms of evaluations of the North Sea projects that allow for improvements. The chosen method allowed for a guiding, forward-looking survey of the light body of literature to create an overview and definition of the topic as well as generalised considerations for offshore energy hub projects internationally. The relevance of the presented material might be increased if the literature search was slightly expanded and included more meta studies on the specific technological, economic, and ecological aspects of the projects.

CRediT authorship contribution statement

Alexandra Lüth: Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Dogan Keles:** Formal analysis, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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