

Review article

Interdisciplinary perspectives on offshore energy system integration in the North Sea: A systematic literature review

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ABSTRACT

To facilitate the rapid and large-scale developments of offshore wind energy, scholars, policymakers and infrastructure developers must start considering its integration into the larger onshore energy system. Such offshore system integration is defined as the coordinated approach to planning and operation of energy generation, transport and storage in the offshore energy system, across multiple energy carriers and sectors. This article conducts a systematic literature review to identify infrastructure components of offshore energy system integration (including alternative cable connections, offshore energy storage, and power-to-hydrogen applications) and barriers to their development. An interdisciplinary perspective is provided where current offshore developments require not only mature and economically feasible technologies, but equally strong legal and governance frameworks. The findings demonstrate that current literature lacks a holistic perspective on the offshore energy system. To date, techno-economic assessments solving challenges of specific infrastructure components prevail over an integrated approach. Nevertheless, permitting issues, gaps in legal frameworks, strict safety and environmental regulations, and spatial competition also emerge as important barriers. Overall, this literature review emphasizes the necessity of aligning various disciplines to provide a fundamental approach for the development of an integrated offshore energy system. More specifically, timely policy and legal developments are key to incentivize technical development and enable economic feasibility of novel components of offshore system integration. Accordingly, to maximize real-world application and policy learning, future research will benefit from an interdisciplinary perspective.

1. Introduction

The North Sea has long played an important role in the energy system of the surrounding states. From the 1960s onward, the North Sea has been used for the exploration and exploitation of hydrocarbons, and since the early 2000s, its coastal states have increasingly been looking at options to exploit offshore renewable energy resources to reduce greenhouse gas emissions as part of a joint effort to limit the global temperature increase [1,2]. To this end, North Sea states have committed to installing up to 300 Gigawatt (GW) of offshore wind energy by 2050 [3]. While this commitment alone is impressive, it is further challenging taking into account that the North Sea is one of the busiest oceans globally, with a wide variety of human activities, among others including shipping, fisheries, areas for military exercises and nature protection. Moreover, the intermittent nature of wind energy,

and already congested onshore grids at potential landing points [4], places significant pressure for the tenfold increase of the installed offshore wind capacity in 2023 [5].

An efficient and effective large-scale roll out of offshore wind energy thus requires scholars, policymakers, and industry professionals to look beyond the current focus on energy generation. It is crucial to emphasize the importance of flexibility and robustness in an (offshore) energy system that becomes progressively more integrated in the future concerning energy generation, transport, and storage. However, offshore energy system integration is underexplored in the current academic literature. The concept is often only implicitly discussed or remains ambiguously defined [6,7]. Based on the more general description of energy system integration as defined in the EU Strategy on Energy

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List of Abbreviations

AC	Alternating Current
DC	Direct Current
ESS	Energy Storage Systems
GW	Gigawatt
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
OWF	Offshore Wind Farm
SNG	Synthetic Natural Gas
TSO	Transmission System Operator
VRES	Variable Renewable Energy Storage

System Integration [8], this paper conceptualizes offshore energy system integration as follows:

Offshore energy system integration is the coordinated approach to planning and operation of energy generation, transport and storage in the offshore energy system, across multiple energy carriers and sectors.

Not only can an integrated offshore energy system improve the system's overall operational efficiency, but it can also enhance economic and environmental performance by sharing (parts of) its infrastructure, human capital, products, and knowledge [8]. This was already recognized by the Dutch government in their latest tender for a new Offshore Wind Farm (OWF) by explicitly stating that a successful bid must contribute to the integration of the OWF into the Dutch onshore energy system [9]. However, these real-life examples are rare and largely limited to individual projects or initiatives. Similarly, existing research on offshore energy systems predominantly focuses on the integration of individual technologies to optimize offshore energy systems from technical and/or economic perspectives. However, it is equally crucial to establish robust and enabling legal and governance frameworks and adopt an overarching sea-basin-scale perspective in the development of an integrated offshore energy system.

To provide this holistic view of the academic knowledge on offshore energy system integration, a systematic literature review is conducted to explore potential components of integrated offshore energy systems and identify barriers hindering their development from technical, economic, legal, spatial planning and governance perspectives. Choosing these disciplines is justified for the following reasons: (1) technical expertise is essential for understanding the technical feasibility, reliability, and performance aspects of offshore energy systems, including their design, construction, and operation; (2) economics plays a central role in assessing the financial viability and cost-effectiveness of offshore energy projects, which is vital information for policymakers and investors to make informed decisions; (3) understanding the legal dimension is needed to navigate the often complex regulatory frameworks governing offshore energy development; (4) a spatial planning and governance perspective addresses the institutional frameworks and rules guiding the allocation and coordination of the offshore energy system, which are crucial for establishing clear guidelines and incentives for the development of an integrated offshore energy system. Incorporating these four perspectives also enables a discussion on how barriers from all disciplines intersect or affect each other. This paper therefore provides a relevant interdisciplinary overview of the current status of academic knowledge on offshore energy system integration and proposes key pathways and challenges for future research.

The North Sea is a highly relevant sea basin for studying the concept of offshore energy system integration. Not only is it one of the world's busiest offshore areas, but the North Sea also presents a hotspot for this transformation of the offshore energy system. The Esbjerg and Ostend Declarations demonstrate the explicit commitment for offshore energy

system integration made by several North Sea states to accelerate the energy transition [3,10]. Taking the North Sea as an exemplary region provides a first effort to gather valuable insights that may be applied to other sea basins with similar boundary conditions awaiting similar developments. Particularly, insights may be applied to other historically intensively used offshore regions bordered by multiple coastal states, where a wide variety of human activities and interests intersect.

This conceptualization of offshore energy system integration allows for the inclusion of a wide variety of infrastructure components for generation, transport and storage. The review specifically focuses on generation by offshore wind energy given the planned large-scale roll out of offshore wind energy in the coming decades, its technological maturity, and explicit commitments in (inter)national policies and declarations [3,11]. The infrastructure required for offshore wind is most likely to form the basis on which a future energy system of the North Sea is further developed. Nevertheless, it is recognized that combinations with other renewable offshore electricity generation technologies – such as wave, tidal, floating photovoltaic, or marine current – are gaining traction more recently [12–14]. Because these have not yet attained similar level of technological readiness, nor received similar explicit commitments for development in policy or by decision-makers across the North Sea region, they are outside the scope of this literature review.

This review explores the following potential transport and storage infrastructure components of an integrated offshore energy system: alternative cable connections, energy storage, and power-to-hydrogen applications. *Alternative cable connections* expand the traditional purpose of offshore cables that transport electricity in only one direction from an OWF to shore. In the future, electricity cables can link multiple OWFs to different national transmission systems, thus, merging the functionality of today's two separate assets (country-interconnectors and radial park-to-shore cables). This could ultimately lead to a meshed offshore electricity grid. *Offshore Energy Storage Systems (ESS)* can help to match electricity supply and demand, and to minimize grid congestion onshore. Integrating *power-to-hydrogen* applications with OWFs not only facilitates the production of 'green', i.e. carbon-neutral, hydrogen but also offers an opportunity to extend the lifetime and use of existing oil and gas infrastructure. This synergy between existing oil and gas infrastructure is particularly interesting for two reasons. Firstly, it prevents the need for further infrastructure investment, as the offshore oil and gas infrastructure is already integrated with the onshore gas storage and transport facilities. As such, the existing infrastructure provides both an opportunity for energy storage and transport. Secondly, it assists oil and gas companies to capitalize on previous investment, providing an incentive to move towards a carbon-neutral business model.

The above mentioned options may reduce the need for additional investments in already congested onshore electricity grids. Considering the extensive development trajectories of offshore infrastructure, using existing infrastructure can also help speed up the roll out of offshore wind energy. All of the aforementioned components of an integrated offshore energy system are still in its infancy and encounter regulatory, economic, or technical obstacles. These three components are relevant to include since they are proposed as promising solutions that offer the desired flexibility and cost-efficiency needed for a future energy system [4,15]. Furthermore, they have received explicit support for development by North Sea states [3].

Overall, this literature review helps researchers and policymakers to improve their understanding of the multifaceted nature of offshore energy system integration, which should be considered to facilitate a transition to a sustainable offshore energy system in the North Sea region and beyond.

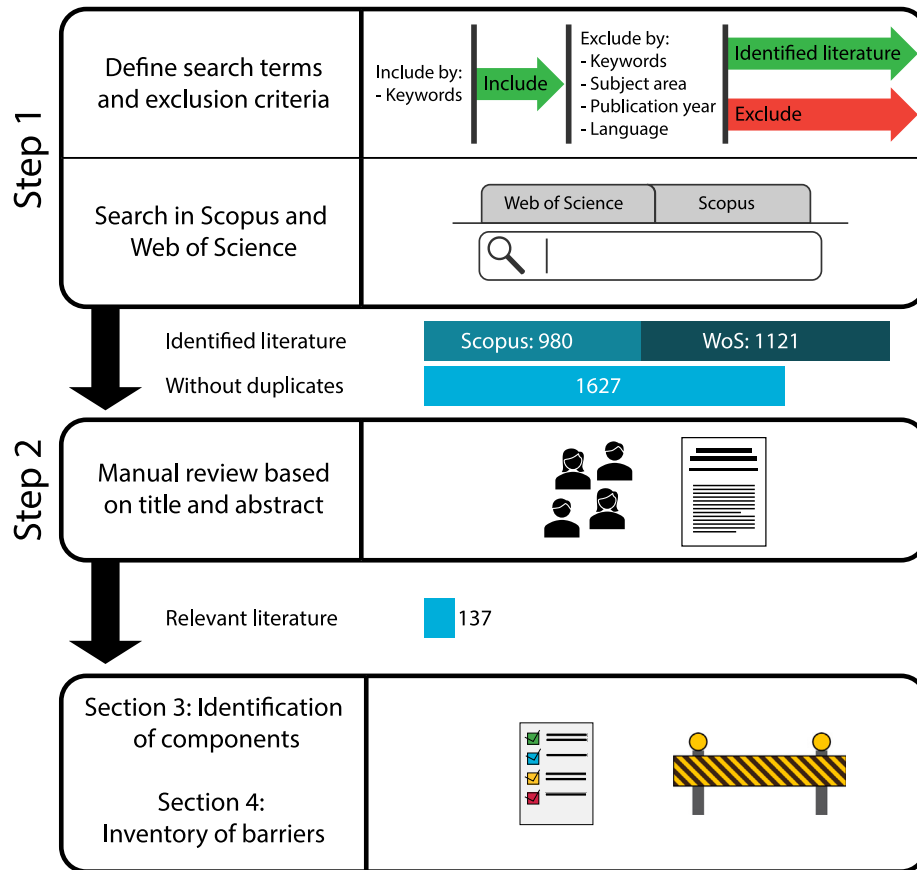


Fig. 1. Search strategy deployed to find relevant literature on offshore system integration. The exact search strategy of step 1 is outlined in Fig. A.1 in the Appendix, including all keywords and exclusion criteria.
Source: made by authors.

2. Methodology

A systematic literature review was conducted to identify essential technological solutions and system components related to offshore energy system integration and to build an inventory of the barriers affecting its large-scale implementation. Involving multiple disciplines facilitated valuable interdisciplinary collaboration and developed a more integrated understanding of the future offshore energy system. In addition, priority areas for further research were identified [16]. The qualitative approach in this study combined a systematic and transparent data collection process with an open and inductive process to analyze the body of literature [17].

A two-step approach was followed to identify and process relevant academic literature addressing technological components of an integrated offshore energy system and to identify barriers, as visualized in Fig. 1.

In step 1, keywords and search criteria were defined to find relevant literature from two major databases for scientific literature (Web of Science and Scopus [18,19]). To compile the search strings, three different clusters of keywords were used: (1) synonyms for 'offshore' (e.g., maritime, marine, continental shelf, etc.), (2) synonyms for or connected terms to 'energy' (e.g., electricity, power, storage, system integration, etc.) and (3) the term 'wind'. The latter was included in the search query, given the recognition that the large-scale implementation of OWFs is a necessary condition for the offshore development of a multi-energy system. These three clusters of keywords were connected with an 'and' operator to ensure that all resulting publications were

relevant to this study. Only scientific articles published after 2014² in English were included. After a first scan of the results, in- and exclusion criteria were identified based on subject areas and keywords. Publications published in areas that evidently fall outside the scope of this paper were excluded, e.g., from neuroscience, nursing, immunology, and microbiology etc. Phrases in the title or the list of keywords connected to other generation technologies, such as photovoltaic, wave energy, and tidal energy, also lead to an exclusion of the publication. A full representation of the search strategy, including all keywords and exclusion criteria, can be found in the Appendix in Fig. A.1. The search was performed in Scopus and Web of Science, resulting in a database of literature for further manual review. The generated database was last updated in January 2023.

In step 2, irrelevant publications were excluded from the database by manually scanning titles, abstracts and keywords. We excluded publications that focus solely on one of the following points:

- **Technical studies of single technologies** focusing only on the working principles or design of: wind turbines, such as floating or horizontal axis turbines; foundations for fixed-bottom wind

² This year was chosen, because from 2014 onward offshore wind energy became a major driver for the energy transition and system integration started to become an issue. For example, in 2014 Germany's cumulative installed capacity passed the 1 GW mark and a new amendment was passed to their renewable energy law making offshore energy an integral part of Germany's energy strategy. In the same year, the Netherlands passed their Wind Energy at Sea Act [20] and published a new roadmap for wind energy developments.

turbines; siting or cable layouts of OWFs; marine current energy; wave energy; tidal energy; floating solar energy; power transmission (AC and DC).

- **Studies of the marine ecosystem** encompassing topics such as the impact of OWFs on marine life.
- **Studies on the forecast of renewable production** using weather data.
- **Studies on carbon emission reduction options for shipping** including new fuel types or wind-driven solutions.
- **Studies on carbon reduction options for seaports** by integrating seaport with renewable and/or storage technologies; or connecting berthed ships to the onshore electricity grid.
- **Studies on estimating the potential of offshore wind for different regions** by using historical or estimated future data on wind speeds at different locations.
- **Studies on the electrification of offshore oil and gas platforms** connecting them either to the onshore grid or to OWFs located close by to reduce the emission intensity of the platform.

Following this manual exclusion process, 137 publications were identified as relevant to this study. The remainder of this paper draws upon this body of literature, which is listed in Table B.2 in the Appendix including an identifier for the respective topic. An Excel table including further information is provided as online Supplementary Information. All relevant publications were fully read and analyzed considering their technological contributions to offshore system integration and barriers in the implementation thereof.

3. Infrastructure components of offshore energy system integration

This section starts by describing the concept of offshore energy system integration and how it is portrayed in the academic literature. It is followed by a reflection on the three main components of offshore energy systems identified in the literature: (1) electricity cable connections, (2) ESS, and (3) power-to-hydrogen applications.

3.1. Offshore system integration

As stated, literature treats the concept of system integration only implicitly. Namely, many studies provide techno-economic assessments of specific combinations of technologies for system integration evaluating, *inter alia*, the coupling of storage and transport infrastructures [21–23], the assessment of energy hubs or artificial islands [24–26], and the integration of power-to-hydrogen, hydrogen storage and transport [27,28]. In contrast, issues of offshore energy system integration from a legal or governance perspective remain largely unexplored. However, existing research does provide relevant insights on multi-use of ocean space [29,30] or environmental procedures for offshore infrastructures [31,32] that can be applied to the concept of offshore system integration.

3.2. Electricity cable connections

Traditionally, offshore electricity cable connections were categorized either as interconnection cables between two different countries (*interconnectors*) or connection cables to OWFs (*park-to-shore cables*). This configuration is illustrated in Fig. 2(a). The enormous growth of offshore wind energy projected for the next decades and its expected allocation further offshore calls for a new design of offshore electricity transmission. As a first step, the introduction of multi-purpose interconnectors is possible. These multi-purpose interconnectors serve as both interconnectors between two countries and as a means to transport electricity from OWFs to shore (see Fig. 2(b)). In the long term, the offshore grid is expected to move towards a meshed grid, connecting both wind farms and various national onshore grids, as illustrated in 2(c) [33]. Hence, the traditional separation of interconnectors and

park-to-shore cables is expected to be combined in the future. These meshed grids come with various benefits: (1) higher cable utilization suggesting lower connection costs for OWFs, (2) minimizing curtailed energy from OWFs as they are connected to multiple onshore grids, (3) offering an additional option to exchange electricity between different regions to stabilize prices and enhance security of supply [23,27,33,34]. Onshore transmission grids are largely based on High Voltage Alternating Current (HVAC). This means of transmission, however, is not suitable for longer distances as is typically the case offshore. In a review by Elliott et al. [35], it is argued that offshore electricity transmission above a certain distance is only economically feasible with High Voltage Direct Current (HVDC) cables. As such, there are studies that specifically focus on the comparison of Alternating Current (AC) and Direct Current (DC) transmission options for specific use cases [35–37].

Fig. 3 shows three different common options for electricity transmission between an OWF and the onshore transmission system. For OWF located close to shore, AC transmission at higher voltage is feasible. This option requires a transformer platform offshore and onshore to reach the transmission voltage levels required (see Fig. 3(a)). This is a common way for transmission up to 90 km, depending on the use case [35]. In recent years, as OWFs move further offshore, electricity losses become unacceptable and new means of transmissions are required. A theoretical option is low-frequency transmission as shown in Fig. 3(b) [38]. In this option, transmission losses are reduced by increasing voltage at a lower frequency than the onshore grid. As the collection grid has the same frequency as the transmission line, a converter station offshore is not required. The most common option for far-distance offshore electricity transmission is HVDC transmission [33,35]. This option requires a converter and transformer station offshore, converting AC power from the wind farm to DC and stepping up the voltage to transmission level. Onshore, voltage and frequency need to be matched again with the onshore transmission grid (see Fig. 3(c)).

To date, there are two major converter technologies available (line-commutated converters and voltage-source converters), both being a major cost-driver for offshore wind developments [28,35,39,40]. While point-to-point transmission with HVDC is an established technology, the operation of multi-nodal DC grids as shown in Figs. 2(b) and 2(c) require additional customized HVDC breakers and fault protection gear to achieve high power transfer security similar to that of AC grids [39,41–43].

In addition to different technical requirements for offshore meshed grids, the governance of these grids also differs from that of onshore grids. A meshed grid with international connections requires multiple actors to collaborate both onshore and offshore. These collaborations are not limited to governmental agencies, but also includes Transmission System Operators TSOs, market operators, investors, and wind farm operators from multiple countries. Given the complexity of such international collaborations, OWFs have historically been connected using park-to-shore cables, involving only one jurisdiction in the licensing and administration of the transmission line. The current legal literature predominantly focuses on the regulatory regimes needed for meshed grids. Meeus [44] identifies alternative models for the regulation and ownership of grid connections, including the third-party model (prevalent in the UK) and the generator model (i.e. in Sweden). Sunila et al. [45] examines whether a supranational Transmission System Operator (TSO) could facilitate the necessary regional cooperation and coordinate investments. On the other hand, Flynn [46] stresses the large influence of national TSOs on meshed grid developments.

3.3. Energy storage systems

ESS are emerging as a key component for the integration of large-scale Variable Renewable Energy Storage (VRES), such as wind and solar energy, in the offshore electricity grid. Storage technologies can be applied to reduce peak loads in the electricity grid and prevent

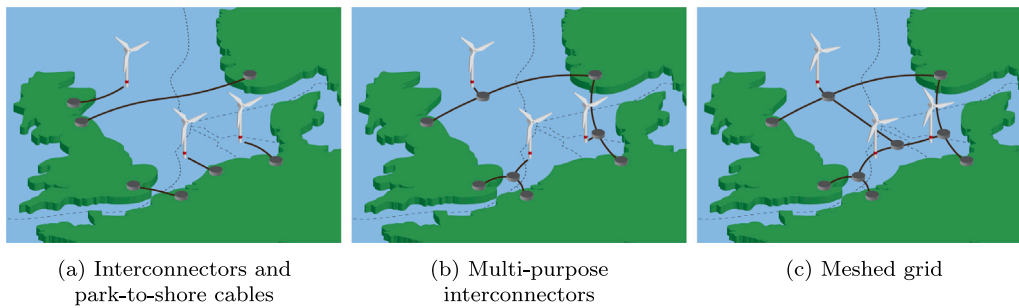


Fig. 2. Offshore electricity cable configurations. Based on [33].

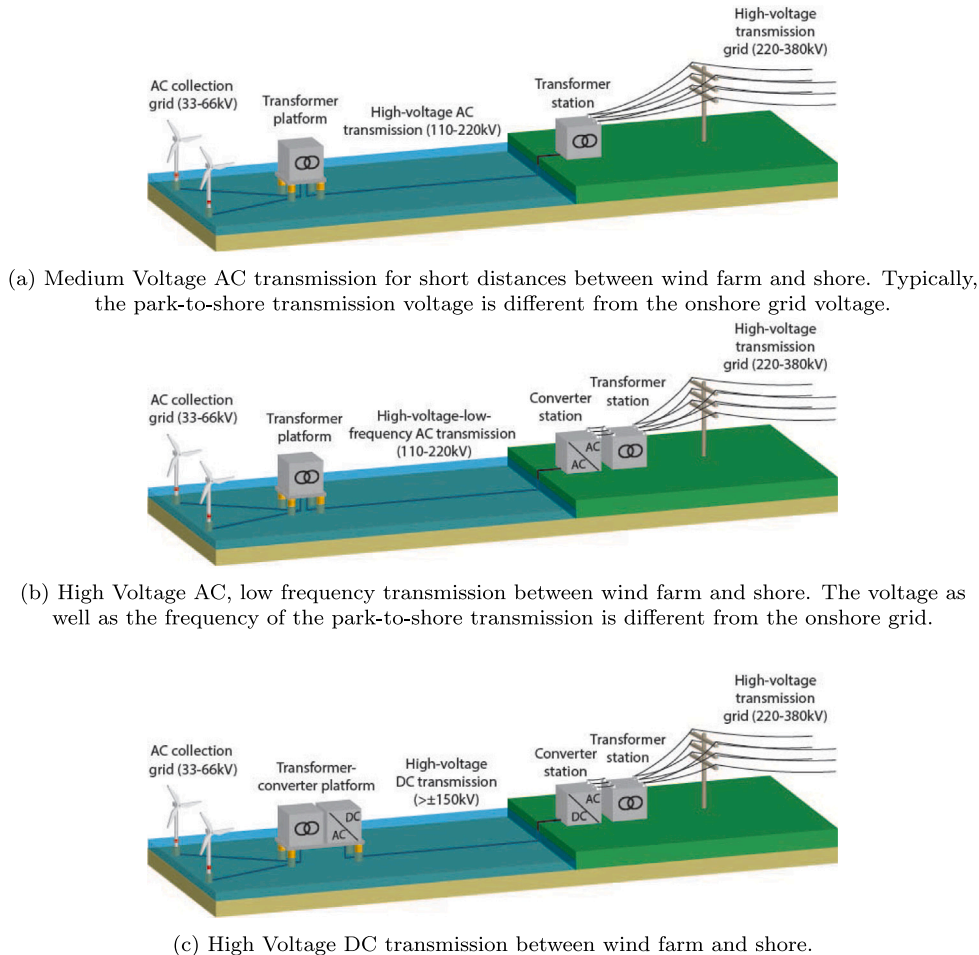


Fig. 3. Electricity transmission technologies from park to shore.
Source: made by authors.

congestion issues. Furthermore, they can facilitate a stable energy supply and greater flexibility in the balancing of the system [23,47,48]. Moreover, long-term energy storage can help compensate for seasonal mismatches between energy demand and supply.

The broad range of application areas for ESS are connected to their specific working principle and performance parameters. An overview of different ESS and their corresponding application is provided in Fig. 4 or by Arellano-Prieto et al. [49]. In principle, all of these ESS technologies can be deployed in an offshore setting, either by mounting it on a dedicated platform or installing it in the surrounding seawater (e.g., underwater on the seabed). Some ESS, however, rely on working principles that are only possible offshore and, thus, considering placing ESS offshore opens up possibilities for new storage technologies. Current literature on ESS highlights particular developments in offshore

electrochemical systems (hydrogen or synthetic natural gas), compressed air energy storage (located onshore) and novel pumped-hydro applications (underwater) in the surveyed literature [50–55].

Current literature on ESS can be distinguished by the following three strands. Firstly, *comparative storage reviews* provide an overview of performance parameters of different ESS focusing on specific working concepts either by comparing performance parameters or highlighting the advantages and disadvantages for specific applications [57–59]. Secondly, *conceptional ESS research* introduces innovative storage technologies by providing a framework to validate its performance. These studies are narrow in scope, defining a set of technical performance metrics (e.g., energy density, round-trip efficiency) [60,61] or economic parameters (e.g., capital cost, operational costs, levelized cost

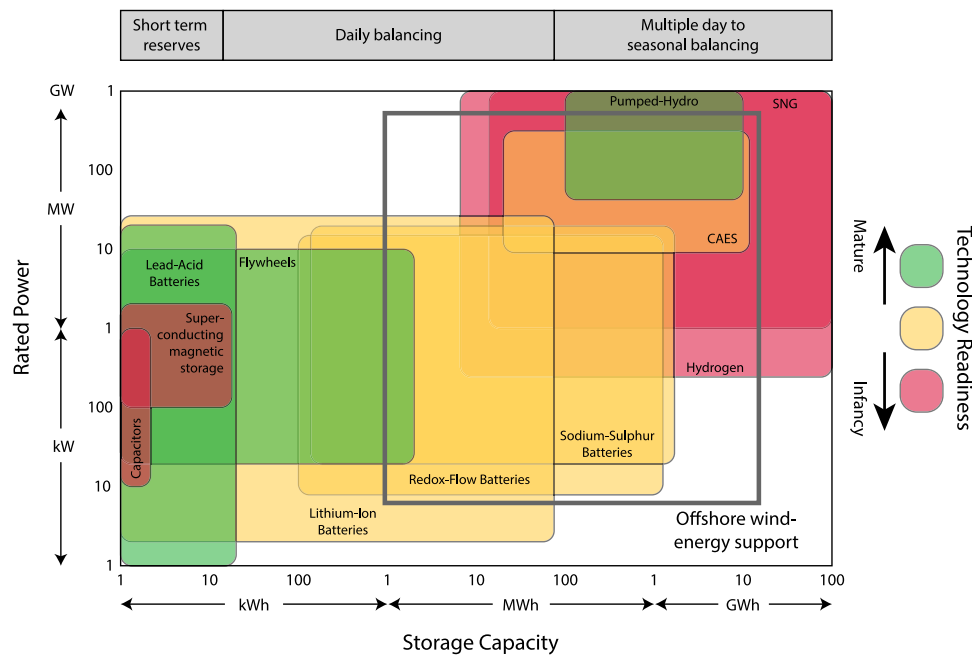


Fig. 4. Comparison of common energy storage systems. SNG stands for Synthetic Natural gas, CAES for Compressed Air Energy Storage. Based on [47,56].

of energy) [62] for the respective storage system. Finally, *ESS integration research* typically looks at the integration of a specific storage technology with offshore wind energy generation (or more general with VRES). In these studies, the focus lies on the operation and/or design of an integrated system highlighting the economic and technical benefits of the ESS [48,52,53,61,63]. Hereby, studies focusing on individual storage technologies serve as a starting point for the system integration perspective, providing high fidelity models that describe cost parameters and provide technical data. However, review studies that incorporate a broader scope, by considering a range of different technologies at system level, ultimately result in a lower level of detail. These studies often highlight and compare a specific area or domain of each system and neglect to deliver on the embedded connections of the larger system. To widen this simplified perspective, it would be beneficial to use a more comprehensive and interdisciplinary approach to identify important factors beyond the technical parameters.

3.4. Power-to-hydrogen and transport pipelines

Hydrogen is expected to play a major role in a low-carbon future as both an energy storage medium and an energy carrier to serve, for instance, increasing industrial demand. One way to provide hydrogen in a carbon-neutral way is through electrolysis, where electricity is converted into hydrogen using renewable electricity. Offshore wind energy is expected to play a pivotal role as the main energy source for this so-called green hydrogen production [64,65]. Furthermore, it enables the deployment of far-shore OWFs due to lower costs and smaller losses of gas transport via pipelines compared to electricity transmission via HVDC cables [66–70]. However, the economic feasibility of offshore hydrogen production compared to onshore hydrogen production is under debate [66,67,71], and thus the feasibility of deploying electrolyzers offshore is widely studied [65,72–75].

Hydrogen production in combination with geological gas storage can offer additional storage capacity if the stored hydrogen is re-converted into electricity. The storage of hydrogen is possible in salt caverns, which have been in use for many decades primarily for storing natural gas. It is important to note that such salt caverns and the necessary infrastructure are only available onshore, and it is unlikely that offshore hydrogen storage will be practical in the foreseeable future.

Offshore depleted oil and gas reservoirs, however, are not suitable for the storage of pure hydrogen. [76,77].

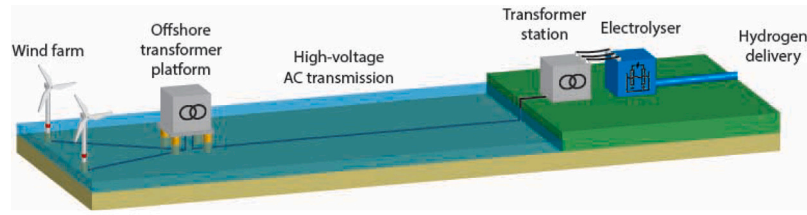
Four potential future scenarios for green hydrogen production offshore and its transport to shore are foreseen [66]: (1) centralized hydrogen production onshore with renewable energy from OWFs directly connected via an electricity cable (Fig. 5(a)); (2) production of hydrogen on existing offshore gas platforms and transport to shore via existing gas pipelines already connected to such platforms (Fig. 5(b)); (3) production of hydrogen on new platforms and transport to shore via new pipelines (Fig. 5(c)); and (4) decentralized offshore production of hydrogen within individual offshore wind turbines (Fig. 5(d)).

The third and fourth scenario are of particular relevance where projected OWFs are not located in the vicinity of existing offshore gas platforms or where such platforms cannot accommodate a hydrogen infrastructure. Scenarios two, three and four eliminate the need to lay new electricity cables to shore and offer an opportunity for re-conversion of hydrogen to electricity. Similar technological configurations can also be utilized for more general power-to-X applications, such as ammonia or synthetic natural gas.

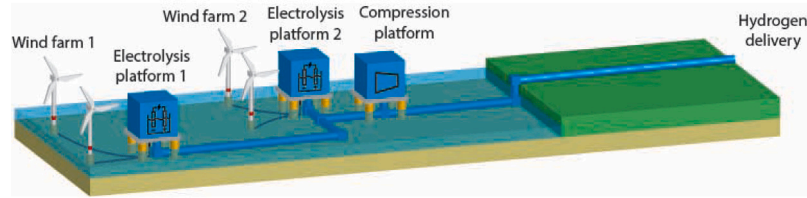
In the second scenario, existing offshore gas platforms can be electrified to enable the production of green hydrogen. Electrification of such platforms has been analyzed extensively in the literature [78–81] as an option to, *inter alia*, reduce emissions from offshore hydrocarbon operations [82–84], but also for offshore green hydrogen production [66, 85,86]. Furthermore, electrification of such platforms and the reuse of existing hydrocarbon infrastructure is considered in several research and pilot projects [87], especially as it postpones the high decommissioning costs of offshore gas platforms incurred by several coastal states and it extends the economic lifetime of existing pipelines connected to these platforms [88,89]. As such, future scenarios for offshore (green) hydrogen production, storage and transport involve the integration of three offshore energy subsystems: offshore wind, offshore gas and offshore hydrogen infrastructure.

4. Inventory of barriers to the development of an integrated offshore energy system

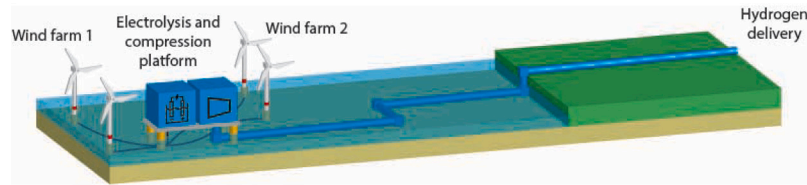
This section provides an inventory of technical, economic, legal, (spatial) planning and governance barriers that hinder the development of offshore energy system integration and corresponding infrastructure



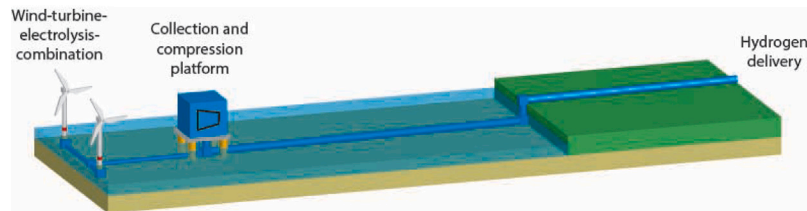
(a) Scenario 1: Onshore hydrogen production. Electricity transmission can be implemented with any of the technologies presented in the previous section (i.e. AC or DC).



(b) Scenario 2: Distributed electrolysis and compression on existing oil and gas platforms. Transport pipelines are repurposed from existing oil and gas infrastructure.



(c) Scenario 3: Centralized electrolysis and compression on a new platform or artificial energy island. Transport through newly build pipelines.



(d) Scenario 4: In-turbine electrolysis with a collection and compression platform. Platform and pipelines can be newly built or repurposed

Fig. 5. Pathways for hydrogen production from offshore wind.
Source: made by authors.

components. The specific barriers are presented in Table 1 for easy reference and discussed in the remainder of this section.

4.1. Techno-economic barriers

4.1.1. Electricity cable connections

As described in the previous section, a meshed offshore grid offers significant benefits regarding the integration of offshore wind. However, these benefits are not shared equally amongst the relevant actors and countries. Gorenstein Dedecca et al. [96] specifically studies the asymmetry of costs and benefits of a North Sea offshore electricity grid. They conclude that costs and benefits of offshore grid expansion are unevenly distributed to a high extent between the relevant actors and participating countries. As a result, some countries may refuse to cooperate in the planning process in order to minimize their own losses, despite the negative impact on overall social welfare. This can lead to further complications in the planning of offshore grid expansion and reinforce undesired path dependencies [23,96].

Transmission with AC connections is not viable over long distances, as typically required in an offshore context. HVDC transmission is a promising alternative, related to less energy losses per kilometer. To

date, there is little experience with this type of electricity transmission as the current application area is mostly limited to point-to-point connections. This limited experience in combination with additional required equipment (i.e. converters) compared to HVAC transmission results in higher investment and operating costs [28,35,36]. Additionally, some of the equipment required for HVDC connections is not yet manufactured on a large scale, causing unanticipated delays [23,34,98]. Despite higher capital expenditure, choosing for HVDC transmission is still worthwhile due to the mentioned lower losses. In the past, OWF developers and TSOs have invested in less suitable AC transmission for a specific project as they were not yet experienced with HVDC options [35,39]. In the long term, meshed DC grids are envisioned for the North Sea. In 2015, however, only two HVDC grids – each with three nodes – were in operation worldwide (Italy–Corsica–Sardinia and Quebec–New England) [39]. These HVDC grids require additional fault protection gear, such as circuit breakers, to achieve similar grid security levels as for traditional AC grids [23,40,43]. These fault protection gear makes meshed HVDC grids even more expensive and difficult to design and/or operate.

Table 1

All barriers to offshore system integration identified in literature. The table is sorted by field and component.

Field	Component	Barrier	Description	Example Reference
Technical	Electricity cable connections	Electricity transmission — Losses	With increasing distance to shore, electricity transmission losses become larger.	[90]
Technical	Electricity cable connections	Electricity transmission with HVDC — Industrial availability of fault protection gear	Fault protection gear for meshed HVDC grids is not yet available at an industrial scale.	[40,43,91]
Technical	Electricity cable connections	Electricity transmission with HVDC — Limited experience	There is a very limited experience with meshed HVDC grids (only two grids in operation worldwide). Other HVDC lines are point-to-point.	[35,39,43]
Technical	Power-to-Hydrogen	Green hydrogen production offshore	Operation and maintenance of offshore hydrogen production is difficult.	[87]
Technical	Power-to-Hydrogen	Green hydrogen production offshore — Water supply	Sea water needs to be cleaned and desalinated for electrolysis, requiring additional equipment offshore.	[87]
Technical	Power-to-Hydrogen	Hydrogen transport	Hydrogen has a low volumetric energy density. Transport in gaseous form requires large pipelines/transport containers.	[92]
Technical	Power-to-Hydrogen	Hydrogen transport — Diffusivity and embrittlement	Hydrogen is an aggressive chemical element and pipelines and other equipment deteriorates quicker. Additionally, hydrogen can diffuse through material more easily than natural gas.	[73,93]
Technical	Power-to-Hydrogen	Hydrogen transport — Pressure drop	Long-distance hydrogen transport leads to large pressure drops in the pipelines, requiring additional compression steps.	[87]
Technical	Energy storage systems	Uncertain performance of immature storage technologies	Energy storage systems for offshore applications are immature and not tested on a large scale. Their long-term performance is thus unknown.	[53]
Technical	System integration	Operation of an integrated energy system under uncertainty	Operation of energy systems with high fluctuations and uncertainties from intermittent wind generation remains challenging (grid and technology operation)	[48,91]
Economic	Electricity cable connections	Cost of offshore electricity transmission	High cost of offshore electricity transmission. Additional cost increase for DC transmission compared to AC transmission.	[37,92,94,95]
Economic	Electricity cable connections	Cost of HVDC offshore electricity transmission — Cost of fault protection gear	Fault protection gear in meshed grids is more expensive than in AC grids.	[40,43]
Economic	Electricity cable connections	Distribution of costs and benefits — Between consumer and producer	Costs and benefits of electricity grids are not equally distributed between producers and consumers. The resulting incentive structure hinders the development of an offshore grid.	[96]
Economic	Electricity cable connections	Distribution of costs and benefits — Between jurisdictions	Costs and benefits of electricity grids are not equally distributed between jurisdictions. The resulting incentive structure hinders the development of an offshore grid.	[25,96]
Economic	Power-to-Hydrogen	Cost of green hydrogen production	Uncertainty of future production and transport cost and market prices, market price today too low for hydrogen business case, electrolysis and means of transport too expensive today	[6,22,57,68,73,74,87]
Economic	Power-to-Hydrogen	Cost of hydrogen transport — Repurposing of offshore oil and gas infrastructure	Cost of re-purposing pipelines and platforms is highly uncertain	[6]
Economic	Power-to-Hydrogen	Imperfect international hydrogen market	Hydrogen is currently not traded internationally. Thus no uniform price exists, increasing uncertainty for investors and thus delaying large-scale investment.	[68,73,92]
Economic	Power-to-Hydrogen, Storage	Cost of hydrogen storage	Hydrogen storage is too expensive for power-hydrogen-power applications (as required for seasonal storage)	[55]
Legal	Electricity cable connections	Fragmented national legal frameworks — Cross-border infrastructure	National regulatory frameworks governing electricity transmission are often incompatible	[44,45,96,97]
Legal	Electricity cable connections	Fragmented national legal frameworks — Support schemes	Heterogeneous national subsidy schemes for offshore renewable energy projects make cross-border trade difficult to support.	[25,98]

(continued on next page)

Table 1 (continued).

Field	Component	Barrier	Description	Example Reference
Legal	Electricity cable connections	Inadequate regulation — Cross-border infrastructure	Regulation governing cross-border electricity infrastructure does not support the integration of interconnectors with park-to-shore cables (e.g., 70% rule)	[97]
Legal	Electricity cable connections	Inadequate regulation — Separation of transmission and generation planning	Regulation inadequate for integrated transmission/generation planning	[96]
Legal	Electricity cable connections	Lack of legal framework — Classification of offshore cables	Adopted definitions of offshore cables indicate that they belong to a specific activity discouraging the sharing of such cables	[45,99]
Legal	Electricity cable connections, Power-to-Hydrogen	Lack of legal framework — Harmonization and standardization	International guidelines, norms and safety standards for hydrogen production/transport and electricity transmission is required	[23,65,94]
Legal	Electricity cable connections, Power-to-Hydrogen	Lack of legal framework — Third party access to offshore transport infrastructure	Third-party access to offshore hydrogen transport and electricity transmission infrastructure is not regulated	[99]
Legal	Power-to-Hydrogen	Lack of legal framework — Classification of offshore pipelines	Absence of clear guidance on the classification of offshore pipelines and the extent to which they are regulated varies between countries	[99]
Legal	Power-to-Hydrogen	Lack of legal framework — Support schemes	Lack of support schemes and certification schemes for green hydrogen production	[22,25,100]
Legal	System integration	Inadequate regulation — Public participation	Participation in consultation processes for major offshore infrastructure is limited by the respective governance framework.	[101]
Legal	System integration	Lack of legal framework — National renewable and carbon quotas	Internationally transported energy needs to be counted in a respective national carbon and/or renewable quota. Clear rules are missing	[25]
Governance	System integration	Divergent national governance frameworks	National focus of planning processes and national differences between environmental licensing requirements and planning of offshore generation and transmission complicate development of cross-border infrastructures.	[23,32,96,102]
Governance	Electricity cable connections	Separation of transmission and generation planning	Not all technologies are considered, planning of grid and generation expansion is conducted by different actors.	[96]
Governance	Electricity cable connections	Priority of national interest	National policy decisions are prioritized over international, cross-border collaboration and infrastructure. TSOs and EU have limited competence to initiate cross-border infrastructure	[45,46,94,96,99]
Governance	Electricity cable connections	Public perception and acceptance	Limited knowledge of offshore technologies and potential spatial conflicts with other industries (e.g., fishing) might spark public opposition	[103]
Governance	General	Spatial competition	Conflicting spatial claims with other ocean uses, such as fishing, military and shipping.	[30]
Governance	General	Diverging national narratives	Different national preferences for technology pathways result in different national innovation systems that might not be compatible with each other in an international cooperative project	[104]
Governance	General	Sectoral focus of planning processes	Planning processes used to be single sector-focused and institutions are still structured respectively. Marine spatial planning however, requires cross-sectoral participatory processes, which are difficult to implement in this institutional context	[29]
Environmental	General	Uncertainty of environmental impacts	Impact of offshore energy infrastructure on marine life is difficult to survey and thus largely unknown.	[31,47,50]
Environmental	Power-to-Hydrogen	Discharge of brine as residual from electrolysis	Large scale electrolysis leads to a large amount of brine that needs to be discharged. Environmental permitting as well as the impact on the environment is uncertain.	[87]
Other	Electricity cable connections	Delays from supply chain shortages	Shortage of required equipment for an offshore HVDC grid delays construction (specifically DC breakers)	[98]
Other	Power-to-Hydrogen	Area requirements for offshore hydrogen production	Industrial scale electrolysis has much higher area requirements than typically available on conventional offshore gas platforms	[95]

4.1.2. Energy storage systems

A large share of the literature suggests ESS as a solution to integrate large-scale offshore wind in the energy system of the North

Sea states. These studies emphasize the capability of storage to add flexibility to the system as well as contributing to its resilience. Offshore installations, especially foundational structures, need to be protected

from degradation mechanics, such as bio-fouling and scouring, which requires a more conscientious design approach compared to their onshore counterparts [71]. Furthermore, additional safety factors and adapted maintenance schedules are required in order to prevent costly breakdowns. The maintenance itself is costly due to the difficulty to transport equipment to the storage site and additional safety measures required for personnel. All of these factors increase the investment and maintenance costs of offshore storage technologies in comparison to their deployment onshore [46].

The uncertainty of the design of a future offshore system makes investment decisions into offshore ESS very difficult. Required capacities and locations are unknown, but needs to be matched with a currently unknown energy system design [51,105]. However, challenges of realizing energy storage in a harsh marine environment are often overlooked or fall outside the scope of these publications. Moreover, there is a general lack of experience with ESS system installation and operation offshore, as no large-scale system has been installed thus far. Consequently, financial institutions and investors are reluctant to provide loans and development support in the development stages of newly emerging energy storage concepts applicable to the offshore environment [71].

4.1.3. Power-to-hydrogen and transport pipelines

Different configurations exist for hydrogen production offshore (see Fig. 5). The prevailing configuration of the future is presently unknown and will most likely depend on project-specific factors. The most prominent barrier of integrating hydrogen production together with offshore wind is its production costs. Production costs of hydrogen from electrolysis is currently not competitive with hydrogen produced from natural gas, even when additional costs resulting from offshore installations are not included [6,68]. This finding might change in the future, with rising natural gas and emission prices on the one hand and falling electrolysis costs in combination with decreasing electricity costs from OWFs on the other hand [57,73]. In addition, the re-purposing of otherwise obsolete oil and gas platforms could be a game changer for both production and transport of hydrogen produced offshore [70,106]. However, financial support for (offshore) green hydrogen production, similar to the subsidy schemes for renewable electricity, is lacking [22]. Hou et al. [55] further stresses that today's electricity price fluctuations are not enough to provide a (near-future) business case for power-to-hydrogen-to-power applications, i.e. storing hydrogen for re-conversion into electricity at a later point in time. As such, hydrogen can play a role in minimizing curtailment of wind energy production and thus help to decarbonize industrial processes by providing a green fuel. However, it will most likely not contribute as a storage option in the near future. Given the inherent variability of wind energy production, electrolyzers following the electricity generation of an OWF will likely have a low capacity factor. A more steady production of the electrolyzer can be achieved by over-sizing the wind farm in relation to the electrolyzer [75]. However, this would lead to curtailment during periods when generation from the OWF exceeds the maximum feed to the electrolyzer. Consequently, the coupling of electrolysis with fluctuating wind generation remains an economic challenge.

Also on the demand side uncertainties exist, slowing down investment into green hydrogen production significantly. Babarit et al. [92] and Franco et al. [73] highlight that hydrogen is not traded internationally today, and hence there is no market price serving as an investment incentive. Missing certification schemes for the origin of hydrogen further impair the development of a global hydrogen market [22]. In addition to the economic barriers, a number of technical challenges related to the transport and production of hydrogen remain unsolved. The transport of hydrogen with existing infrastructure requires major adaptations or exchange of compressor and expansion terminals. Additionally, it needs to be ensured that existing pipelines can also be operated with hydrogen. Diffusivity of hydrogen through the pipeline walls as well as embrittlement of the material are known issues of

hydrogen transport [73,93]. Moreover, due to the low volumetric energy density of hydrogen, a change in the pressure regime of existing gas transport infrastructure would be required increasing the energy requirements for transport [73,92].

To date, direct electrolysis of sea water is still in its infancy of development and conventional electrolyzers require clean fresh water that needs to be produced locally [107]. The clean fresh water can be provided by a mature desalination plant installed in close proximity to the electrolysis unit. The share of cost and energy requirement of this additional desalination is only marginal compared to the electrolysis step, and thus is mostly ignored in literature [108]. However, space requirements and the discharging of brine into the ocean water currently have an unknown effect on the local environment with uncertain permitting procedures [87]. Gondal et al. [95], for example, have calculated the area requirements for electrolysis and concluded that the theoretical area footprint of industrial-size electrolysis is much larger than conventional oil and gas platforms. The study suggests that for large scale offshore electrolysis, only reusing existing platforms will not be enough.

4.2. Legal barriers

The feasibility of developing an integrated energy system offshore must also be assessed from a legal perspective. Without legal certainty, investments will not be made, and new developments will not take place. While technology usually requires the law to keep abreast of rapidly changing trends, innovative energy technologies and system solutions seem to be evolving at a pace that the law simply cannot keep up with. Correspondingly, legal barriers to the development of specific infrastructure components for offshore system integration remain largely unidentified through the literature review. Hence, it is a barrier in itself that the available literature on this topic predominantly analyzes techno-economic barriers with no or little references to the absence or lack of legislation. More specifically, a recurring problem is that it is not specified where legislation is lagging behind [23,96]. In addition, the lack of clear definitions – e.g., of green hydrogen – in existing legislation is highlighted as a barrier that creates uncertainty as to which rules apply to specific offshore energy infrastructure [45,99].

A large share of the legal literature analyzes legal issues pertaining to the development of offshore electricity generation and transport infrastructure. More specifically, it concerns the design of the legal framework for OWFs and the connected cable infrastructure [45,97–99]. In particular, the issue of incompatible national legal frameworks for cross-border electricity infrastructure is emphasized [25,44,45,96]. Furthermore, reference is made to legal uncertainties regarding the division of operation and responsibilities in a meshed offshore grid [45]. In the case of offshore cables combining interconnection and park-to-shore transport, Nieuwenhout [97] stresses that the existing EU legal framework is not fit for connecting OWFs to multiple countries. Regarding cross-border electricity infrastructure, the issue of nationally-oriented support schemes for renewable energy is also raised [99]. Lastly, delays due to heterogeneous national permitting criteria for a meshed offshore grid is specified as a legal barrier [98].

Although the literature review did not yield any results in terms of specific legal barriers hampering the development of offshore hydrogen, Scolaro [100] does address the lack of support schemes for offshore power-to-hydrogen production. Additionally, the absence of certification schemes for green hydrogen is raised as a legal barrier for its deployment [22]. Nevertheless, legal barriers remain largely unexplored for the development of offshore energy storage in particular and offshore energy system integration in general in academic, peer-reviewed publications. Therefore, it is necessary to properly address legal challenges when considering new technological components for offshore system integration. This would ultimately also increase pressure on policymakers to create legal frameworks that reduce legal uncertainty and, thus, creates a more favorable environment for investment in sustainable energy technologies offshore.

4.3. Spatial planning and governance barriers

To implement and operate an integrated offshore energy system, questions and challenges regarding spatial allocation and implementation, planning processes and governance frameworks must be addressed. First, the spatial allocation for offshore energy infrastructure is mainly dependent on geographical parameters. For instance, offshore hydrogen production is promoted as a way to delay the decommissioning of offshore oil and gas infrastructures (both platforms and pipelines), which is inherently limited to specific locations [95]. However, offshore energy is only one of many human activities offshore: shipping, fisheries, military areas and many more also lay significant spatial claims on the offshore area. The increasing spatial competition only increases the complexity of implementing and allocating offshore energy infrastructures. Namely, as Yates [30] argues, all ocean activities should be appropriately balanced and addressed through multi-actor and multi-level planning and decision-making processes. This is particularly relevant when considering co-locating various (energy) uses in one single area. Additionally, the environmental status of the marine environment is a determining factor in the implementation of offshore infrastructure. Permitting processes generally require developers to show the absence of any significant and/or negative environmental effects, as stipulated by international agreements, as well as EU and national legislation [32]. This is also a legal barrier and combined with the uncertainties and large knowledge gaps surrounding the marine environment, it further complicates the governance of the offshore energy system [47]. Implementation is also hindered by the long development times of offshore infrastructure [28]. For example, the development of OWFs (which by now can be deemed a mature technology) in the Netherlands can take up to 10 years from planning to operational phases. Integral to any planning process is thereby that stakeholders and the general public may comment on plan or project proposals. Public opposition to offshore activities, particularly regarding the locations where they are connected to shore, are found to hold back implementation [103].

Second, (national) planning processes fail to facilitate the holistic and strategic perspective needed to develop a more integrated energy system with meshed grids, sector coupling and/or storage facilities. This emerges from the observation that energy generation, storage and transmission are organized on a largely sectoral basis. To illustrate this, planning processes for energy generation from OWFs and transmission through electricity cables are separately organized with limited interaction [96]. A holistic perspective for offshore system integration should also include cross-border integration, as connecting energy generation, storage and transport does not need to be limited to one jurisdiction. However, current governance and institutional frameworks fail to enable required international collaboration. Gorenstein Dedecca et al. [96] point out the lack of a European-wide governance framework establishing guidelines for decision-making on the expansion of the offshore electricity grid. Wang et al. [109] argue that regional incentives are needed for the development of meshed grids. More generally, Spro et al. [23] and Fitch-Roy et al. [102] emphasize that the incompatibility of national planning contexts complicates cross-border integration. Also, connecting critical infrastructure across borders requires policymakers to take risks of a geopolitical nature into account [87]. Both Flynn [46] and Sunila et al. [45] identify the prioritization of national interests over international collaboration and shared responsibilities as another barrier to cross-border integration. Thereby, the reorganization of ownership and responsibilities to international arenas is a decision of political nature. Nieuwenhout [97] recognizes the political sensitivity of establishing offshore bidding zones to govern meshed offshore grids as a barrier. Jansen et al. [25] observes this political dimension of governance in questions surrounding costs and benefits, i.e., who pays for these cross-border projects and who benefits from them the most? Finally, another barrier stemming from governance frameworks guiding the implementation of offshore energy infrastructure relates to the

diverging power relations among involved actors and questions of ownership. For instance, although TSOs hold little formal responsibility in decision-making on the expansion of the offshore grid, they hold the main body of knowledge that the decision-makers depend on [45]. Van der Loos et al. [104] corroborates that the roles of powerful industry actors either hinder or stimulate innovative development in the offshore energy sector. Nevertheless, similar to the legal research presented, the governance literature provides little insights into the barriers to the broader concept of offshore energy system integration.

4.4. Other aspects — Modeling the design and operation of integrated energy systems

The envisioned high levels of integration results in a complex energy system, both from a design and operational perspective. This is challenging also for optimizing or simulating the design and operation of these complicated systems, as computational power is to date insufficient. Due to this limit, optimization or simulation models have to date focused on isolated elements of integrated energy systems, e.g., wind-hydrogen integration [39,55,69,74,100,106], wind-storage integration [47,52,53,57,59,62,87,110–112], integration involving artificial islands and/or offshore hubs [25,26], or electricity grid layouts [27,33,46,113]. Only the work of Martinez-Gordon et al. [72] deals with a truly integrated energy system as per our definition in the introduction, in which several energy carriers and services are combined [28]. However, in order to do that, the authors had to significantly simplify technology performances and degradation, cost assumptions, spatial and temporal resolutions and governance or legal constraints. Optimal long-term planning (i.e. taking investment decision-making into account) of integrated energy systems, while maintaining a realistic modeling approach, is highly complex and mathematically difficult to solve with currently available computational power. As such, co-optimizing the design and operation of an integrated energy system becomes increasingly challenging as the level of integration increases.

5. Discussion

5.1. Synthesizing identified barriers

The conducted systematic literature review sheds light on various barriers from technical, economic, legal and governance perspectives. Comparatively, the primary focus regarding the reviewed literature has been confined to investigating the technical and economic feasibility of individual energy technologies, as part of an integrated offshore energy system. Consequently, the identified barriers predominantly address their technical and economic feasibility, lacking a more holistic and interdisciplinary approach, which also addresses legal and governance considerations. However, an inventory of legal and governance barriers based on the systematic literature review is a complex effort. These barriers are identified primarily by analyzing policy and legal frameworks, which are not indexed in scientific databases such as Scopus and Web of Science.

Regarding the technical and economic perspectives, this literature review has shown that technical publications are typically solution-oriented, i.e. they identify a problem and outline a solution to that problem. Identified technological solutions are generally still at their infancy, including offshore meshed grids based on HVDC transmission, offshore storage technologies and (offshore) hydrogen technologies (production and transport). Research focusing on an energy system level typically includes only few sectors and technologies, short time-frames and a limited spatial scope. As such, a holistic perspective on the offshore energy system is largely absent.

Techno-economic aspects. The following challenges can be identified for techno-economic research on the development of offshore energy system integration: (1) the large number of possible combinations of

technologies and transport options requires considerable expertise and data, typically unavailable to a single research group; (2) computational power is still a limit when modeling the interaction of different technologies and transport options with reasonable detail; (3) there is no clear evidence that industrial and academic teams elaborately share expertise and data, which further hinders the development of detailed analysis, especially when it comes to cost and performance data of energy technologies. Furthermore, techno-economic literature adopts simplified economic assumptions, typically including deterministic capital expenditures and constant interest rates. Additionally, this cost data is subject to high uncertainties, *inter alia*, because of the lack of high-quality industrial cost estimates. Researchers presenting a novel technological concept may also have an incentive to make optimistic cost estimates to promote their concept. These challenges are not context- or country-specific and extend to similar contexts globally, since they reflect fundamental issues encountered in the field of offshore energy system integration.

Legal aspects. The literature review largely fails to identify challenges associated with the actual development and implementation of the technology. Even if energy technologies and system solutions are technically and economically (almost) feasible, supportive regulatory frameworks and dedicated planning processes are essential for their development. To date, the literature meeting the search criteria lacks clarification of what actually constitutes a legal barrier and what needs to be done to address it. Therefore, it does not provide sufficient insight to identify the most prominent legal barriers to offshore energy system integration. Although it is stressed that current legal frameworks do not provide the necessary support for the aforementioned developments – e.g., by providing legal certainty and, thus, long-term investment security – more specific solutions on what needs to be done to remedy this is lacking. In fact, the lack of studies and actual work on creating the necessary legal frameworks encountered, suggests that the challenge in legal frameworks is even more fundamental than coping with a distant set of challenges; it is simply underdeveloped and understudied.

Future legal research on offshore energy system integration should take EU policy and legal frameworks as a starting point; since the EU has the power, and has used this widely, to adopt a comprehensive set of rules pertaining to the energy system. Hence, legal barriers will predominantly arise at the EU level, but also in national laws transposing EU energy legislation. Relevant EU policy frameworks pertaining to offshore energy system integration include the EU Strategy for Energy System Integration [8] and the EU Strategy on Offshore Renewable Energy [11]. Whereas the former places great emphasis on the development and need for regulation of energy storage and hydrogen as a means of increasing the flexibility and resilience of the energy system, the latter outlines a number of measures to support the development of offshore renewable energy. In addition, the EU Strategy on Offshore Renewable Energy [11] highlights the potential of a meshed grid to connect offshore wind and the offshore development of storage solutions and hydrogen production. The importance of research and development in these areas is stressed, but the strategy also calls for political support and the promotion of international cooperation, including the need to develop adequate EU and national legal frameworks.

The need to adopt a new legal framework, or specific provisions in the existing legal framework, to regulate the new energy technologies and system solutions highlighted in this paper is particularly evident at the national level. In the Netherlands, for example, sectoral laws have been adopted to regulate specific offshore energy activities, such as the Mining Act [114] for offshore hydrocarbon exploration and exploitation and the Wind Energy at Sea Act [20] for offshore wind energy development. However, these laws do not (yet) cover the regulation and certification of new types of offshore energy activities, i.e. electricity storage and hydrogen production (see [115] for a potential framework for hydrogen certification). This creates legal uncertainty for investors and developers, but also for competent

authorities, especially in the context of permitting procedures. Part of this uncertainty is the risk that existing legal frameworks will simply not allow new types of activities to be undertaken. To some extent, guidance can be sought in more general national laws that regulate all types of offshore activities that are not regulated by sectoral laws, such as the Water Act [116]. However, the fact remains that such general laws do not contain tailored rules for specific offshore energy activities. Although the approach of regulating this limited variety of offshore energy activities in sectoral laws has been successful to date, it remains questionable whether this is a legal barrier to the integrated development of multiple offshore energy activities. This is particularly important given the recent commitments of various North Sea states to significantly increase energy activities in the offshore area. In any case, the resulting uncertainties, and even the risk of not being able to implement new types of activities, is a crucial issue that requires fundamental changes and possibly a complete overhaul of the existing legal framework, such as the adoption of a specific national legal framework for all offshore energy activities.

Governance aspects. Similarly, the reviewed spatial planning and governance literature enables only an identification of barriers on a superficial level. This strand of literature largely relies on the availability of real-life situations and practices to learn from. An integrated offshore energy system (in line with the definition proposed in the Introduction) does not yet exist. Even if it would, the national context is a determining factor of its implementation and/or development. As such, it makes it a difficult task to identify concrete and practical barriers hindering cross-border collaboration and an integrated marine governance in the North Sea.

Still, some general pathways for future research can be deduced, which can be similarly applied to other regions developing an integrated offshore energy system. The literature suggests that governance and institutional frameworks should enable a careful balancing of diverging spatial claims and competing interests as well as requiring a coordinated approach to align sectoral planning processes. What this practically entails remains vague and unspecified. Literature on marine spatial planning and governance of offshore energy reveals two factors of particular importance to address. Firstly, due to the lengthy development trajectories and permitting processes for offshore energy infrastructure, a clear long-term vision on the future energy system is essential for its implementation. Path dependencies of large offshore infrastructure require new technological solutions and system components to fit within the existing system. To illustrate this, Andersen [94] shows that given the interdependencies within technical properties of European transmission infrastructure, extensive legal and governance changes are needed to accompany technological change. In other words, technical feasibility is not sufficient when implementing new energy technologies offshore. Rather, to find physical space for new energy technologies, existing legal, economic and governance must be adapted correspondingly. Therein, Spijkerboer [117] calls for additional research on the informal institutions guiding how actors utilize and follow formal regulatory frameworks and policies.

Secondly, the literature review shows a multitude of uncertainties from all disciplinary perspectives, most prominently regarding technical and economic feasibility of the individual system components and their impacts on the marine environment. The common approach to governing under large uncertainties is an adaptive, 'learning by doing' planning approach. However, this is at odds with the need for a strategic and long-term perspective (also as shown in Kusters et al. [118]). Given the technical complexity of constructing any infrastructure in the harsh marine environment and the lengthy planning and permitting processes for offshore activities, a compromise must be found between the competing desires for an adaptive and strategic planning process.

5.2. Methodological limitations

Two main limitations arise from the chosen methodology to identify relevant literature. Firstly, by using prominent academic databases, the present literature review excluded any gray literature, i.e. relevant studies on projects, concepts or applications of offshore energy storage and transport alternatives from industry, governments or non-governmental organizations. Developments in offshore energy are growing rapidly in number and maturity. The slower nature of academic publication is therefore expected to lag behind industrial publication and development. Secondly, a limitation of the literature review is its implicit bias towards certain disciplines. In fact, legal literature largely lacks indexed databases and is thus difficult to find in a systematic way. Hence, it is difficult to compile an inventory of legal barriers. The main sources of legal research on integrated offshore energy systems, such as policies and legal frameworks, are not academic publications and therefore are not included in this literature review. In order to minimize this bias towards the technical and economic perspective, this article relied on the applicable national legal frameworks (and the EU context) to provide a starting point for future research on legal barriers. Future interdisciplinary research might gain valuable insights by expanding the methodological scope to include conventional search engines as well. Although this approach may not comprehensively uncover all relevant literature and is less systematic, it has the potential to provide additional perspectives on developments occurring beyond the confines of academia. Nevertheless, identification of existing barriers and focus areas for the successful integration of large-scale offshore wind energy through novel energy technologies and system solutions provides a valuable starting point for future research on this topic.

6. Conclusions

This paper highlights infrastructure components of offshore energy system integration and identifies related barriers to facilitate large-scale deployment of offshore wind energy. It provides an interdisciplinary systematic literature review to reflect on the current status of academic literature on offshore energy system integration and to outline perspectives and pathways for future research. The literature review demonstrates that the development of an integrated offshore energy system in the North Sea is hindered by technical, economic, legal and governance barriers.

In contrast to other disciplines, the technical literature presents barriers as a starting point for developing isolated technical solutions. These solutions rarely focus on the entire offshore energy system or take an interdisciplinary perspective. Consequently, translating these different technologies into an integrated system model often results in a reduced order approach, where simplifications are made. These approaches do enable theoretical concepts to be analyzed in a realistic environment. However, at the same time they create knowledge gaps that arise in this step by disregarding the additional complexities of overlapping fields of study that should be incorporated. Hence, a greater consideration of the influence of non-technical and/or economic factors on the deployment of technologies, such as permitting issues, safety regulations, environmental regulations, public acceptance, spatial requirements, is essential.

Furthermore, the literature review illustrates that timely policy and legal developments are needed to incentivize and stimulate mature development of new technologies and the integration of the offshore energy system. Consequently, future research should include legal implications and the importance of suitable legal frameworks to enable the development and integration of novel energy technologies and system solutions. Moreover, research should identify a balanced approach to align sectoral planning processes in the face of long-term uncertainties. The lack of legal and governance certainty does not necessarily mean that the aforementioned novel energy technologies and system

solutions cannot be developed and integrated in the North Sea region. However, such uncertainty is likely to hamper its offshore deployment. Although there are various ways to optimize the integration of the offshore energy system from a techno-economic perspective, the configuration of the future offshore energy system is heavily dependent on political priorities. The technical optimization of the offshore energy system will not by itself set the course ahead.

Nevertheless, to ensure informed decisions on the design of the offshore energy system and corresponding regulations, it is essential that technical progress and results from integrated energy system modeling are clearly communicated to policymakers. In that respect, interdisciplinary research is of utmost importance and this literature review underscores the necessity of aligning various disciplines to avoid stagnation in the offshore integration of novel energy technologies and system solutions. The lack of in-depth interdisciplinary understanding is especially evident in the techno-economic literature, which often indicates the need for legal changes without delving further into the underlying legal barriers and possible solutions. Such research can take many forms, from techno-economic assessments taking into consideration policy and legal implications, to system modeling studies based on technical specifications and spatial limitations. Mostly, interdisciplinary research can benefit from researchers from multiple disciplines actually working together in both analyzing system integration and reporting on their findings in gray and academic literature. Consequently, an *integrated* offshore energy system requires *integrated* research and development.

CRedit authorship contribution statement

J.F. Wiegner: Conceptualization, Methodology, Data curation, Writing – original draft, Writing – review & editing, Visualization. **L.M. Andreasson:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **J.E.H. Kusters:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **R.M. Nienhuis:** Conceptualization, Methodology, Writing – original draft, 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

The database of literature has been added as Supplementary Materials as an excel file.

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Appendix A. Search protocol

See Fig. A.1

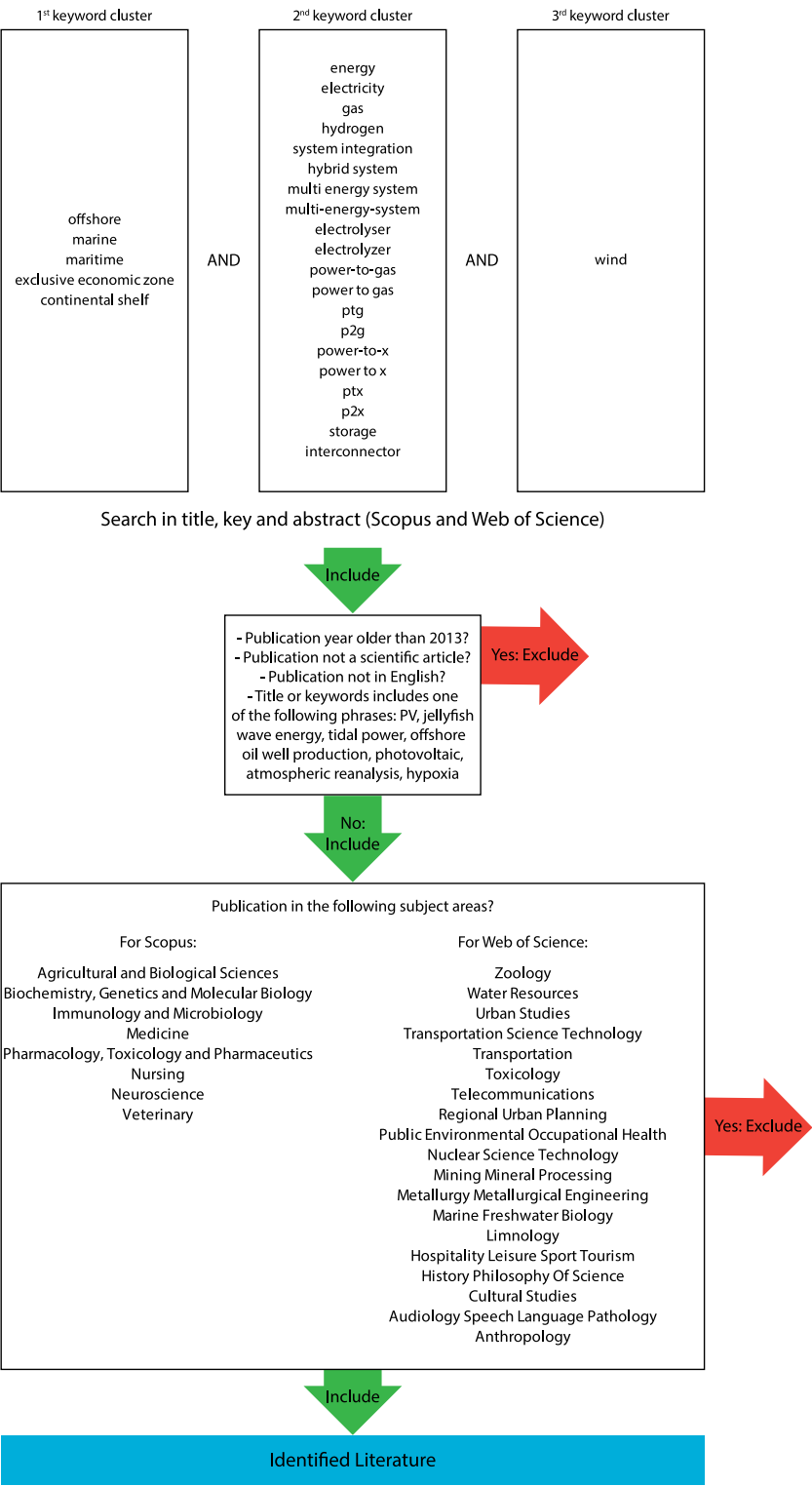


Fig. A.1. Search Protocol for compiling the search strings for Scopus and Web of Science leading to the identified literature database.

Appendix B. Relevant body of literature

See Table B.2

Appendix C. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.rser.2023.113970>.

Table B.2

Barriers to offshore system integration identified in literature.

Title	Reference	Electricity Transmission	Energy Storage	Power-to-Hydrogen	System Integration	Other
Sizing and rough optimization of a hybrid renewable-based farm in a stand-alone marine context	[119]	x	x	x	x	
Unlocking the UK Continental Shelf Electrification Potential for Offshore Oil and Gas Installations: A Power Grid Architecture Perspective	[79]	x	x	x		
Techno-economic feasibility of fleets of far offshore hydrogen-producing wind energy converters	[92]	x	x	x		
Feasibility analysis of an islanded hybrid wind–diesel–battery microgrid with voltage and power response for offshore Islands	[120]	x	x	x		
Energy management of an off-grid hybrid power plant with multiple energy storage systems	[121]	x	x	x		
Synergistic Control Between Hydrogen Storage System and Offshore Wind Farm for Grid Operation	[111]	x	x	x		
A techno-economic assessment of offshore wind coupled to offshore compressed air energy storage	[53]	x	x	x		
Synergies in offshore wind and oil industry for carbon capture and utilization	[95]	x	x	x		
Environmental impacts of balancing offshore wind power with compressed air energy storage (CAES)	[50]	x	x	x		
Development of a viability assessment model for hydrogen production from dedicated offshore wind farms	[105]	x	x	x		
Buoyancy Energy Storage Technology: An energy storage solution for islands, coastal regions, offshore wind power and hydrogen compression	[54]	x	x	x		
A review of marine renewable energy storage	[109]	x	x	x		
Hydrogen production from offshore wind power in South China	[65]	x	x	x		
Techno-Economic Analysis of Low Carbon Hydrogen Production from Offshore Wind Using Battolyser Technology	[57]	x	x	x		
Optimal power flow in multi-terminal HVDC grids with offshore wind farms and storage devices	[39]	x	x			
Blending HVDC-Link Energy Storage and Offshore Wind Turbine Inertia for Fast Frequency Response	[122]	x	x			
North Sea offshore network and energy storage for large scale integration of renewables	[23]	x	x			
A Coordinated Control of Offshore Wind Power and BESS to Provide Power System Flexibility	[112]	x	x			
Offshore Wind Farms Energy Injection in the Electrical Grid-Lithium Battery to Mitigate Power Fluctuations	[48]	x	x			
Liquid metal battery storage in an offshore wind turbine: Concept and economic analysis	[59]	x	x			
Optimal Sizing of Seawater Pumped Storage Plant with Variable-Speed Units Considering Offshore Wind Power Accommodation	[123]	x	x			
Analysis of the wind and wave-induced dynamic response of a floating offshore wind turbine integrating a compressed air energy storage system	[60]	x	x			
Experimental assessment of compressed air energy storage (CAES) system and buoyancy work energy storage (BWES) as cellular wind energy storage options	[51]	x	x			
A fuzzy analytic hierarchy process-based analysis for prioritization of barriers to offshore wind energy	[124]	x	x			
Energy Storage Capacity Planning Method for Improving Offshore Wind Power Consumption	[62]	x	x			
Joint Planning of Offshore Wind Power Storage and Transmission Considering Carbon Emission Reduction Benefits	[21]	x	x			
“We could have been leaders”: The rise and fall of offshore wind energy on the political agenda in Ireland	[125]	x	x			
Roadmap to hybrid offshore system with hydrogen and power co-generation	[68]	x		x	x	

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Table B.2 (continued).

Title	Reference	Electricity Transmission	Energy Storage	Power-to-Hydrogen	System Integration	Other
Hydrogen from offshore wind: Investor perspective on the profitability of a hybrid system including for curtailment	[74]	x		x	x	
Analyzing long-term opportunities for offshore energy system integration in the Danish North Sea	[6]	x		x	x	
Benefits of an integrated power and hydrogen offshore grid in a net-zero North Sea energy system	[69]	x		x	x	
Modeling a highly decarbonized North Sea energy system in 2050: A multinational approach	[72]	x		x	x	
Offshore transmission for wind: Comparing the economic benefits of different offshore network configurations	[33]	x		x		
Integrating Offshore Wind Power and Multiple Oil and Gas Platforms to the Onshore Power Grid Using VSC-HVDC Technology	[78]	x		x		
Regulating Offshore Energy Sources in the North Sea-Reinventing the Wheel or a Need for More Coordination?	[99]	x		x		
Steady-state analysis of a conceptual offshore wind turbine driven electricity and thermocline energy extraction plant	[126]	x		x		
Assessment of offloading pathways for wind-powered offshore hydrogen production: Energy and economic analysis	[73]	x		x		
Improving the energy yield from an open loop hydraulic offshore turbine through deep sea water extraction and alternative control schemes	[127]	x		x		
Sustainable and clean oilfield development: How access to wind power can make offshore platforms more sustainable with production stability	[82]	x		x		
Smart load management of water injection systems in offshore oil and gas platforms integrating wind power	[80]	x		x		
Assessment of renewable energy supply for green ports with a case study	[128]	x		x		
Dynamic performance of a novel offshore power system integrated with a wind farm	[81]	x		x		
Dedicated large-scale floating offshore wind to hydrogen: Assessing design variables in proposed typologies	[87]	x		x		
Hydrogen production from the WindFloat Atlantic offshore wind farm: A techno-economic analysis	[75]	x		x		
Island in the Sea: The prospects and impacts of an offshore wind power hub in the North Sea	[25]	x		x		
Powering Europe with North Sea offshore wind: The impact of hydrogen investments on grid infrastructure and power prices	[24]	x		x		
Techno-economic analysis and Monte Carlo simulation for green hydrogen production using offshore wind power plant	[67]	x		x		
Transporting offshore wind power in the Western Gulf of Mexico: retrofitting existing assets for power transmission via green hydrogen-a review	[88]	x		x		
Robust H infinity control for stability assessment in grid-connected offshore wind and marine current hybrid system	[13]	x			x	
Comparison of Cost-effective Distances for LFAC with HVAC and HVDC in Their Connections for Offshore and Remote Onshore Wind Energy	[36]	x				
A Comparison of AC and HVDC Options for the Connection of Offshore Wind Generation in Great Britain	[35]	x				
Variable AC transmission frequencies for offshore wind farm interconnection	[37]	x				
Optioneering analysis for connecting Dogger Bank offshore wind farms to the GB electricity network	[40]	x				

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Table B.2 (continued).

Title	Reference	Electricity Transmission	Energy Storage	Power-to-Hydrogen	System Integration	Other
Offshore DC Grids as an Interconnection of Radial Systems: Protection and Control Aspects	[43]	x				
Droop Control Design of Multi-VSC Systems for Offshore Networks to Integrate Wind Energy	[129]	x				
A New Wind Turbine Interface to MVdc Collection Grid with High-Frequency Isolation and Input Current Shaping	[130]	x				
Integration of Large-Scale Offshore Wind Energy via VSC-HVDC in Day-Ahead Scheduling	[41]	x				
Multilevel Modular DC/DC Power Converter for High-Voltage DC-Connected Offshore Wind Energy Applications	[90]	x				
Hybrid, Multi-Megawatt HVDC Transformer Topology Comparison for Future Offshore Wind Farms	[131]	x				
Energy curtailment of DC series-parallel connected offshore wind farms	[42]	x				
A Reliability Evaluation of Offshore HVDC Grid Configuration Options	[132]	x				
Expansion planning of the North Sea offshore grid: Simulation of integrated governance constraints	[96]	x				
The Effect of Welfare Distribution and Cost Allocation on Offshore Grid Design	[34]	x				
Integrated Global Optimization Model for Electrical Cables in Offshore Wind Farms	[133]	x				
Minimizing Energy Loss by Coupling Optimization of Connection Topology and Cable Cross-Section in Offshore Wind Farm	[134]	x				
Towards a fully integrated North Sea offshore grid: An engineering-economic assessment of a power link island	[26]	x				
Simultaneous optimization of electrical interconnection configuration and cable sizing in offshore wind farms	[135]	x				
Offshore grids for renewables: do we need a particular regulatory framework?	[44]	x				
A supra-national TSO to enhance offshore wind power development in the Baltic Sea? A legal and regulatory analysis	[45]	x				
Power transmission: Where the offshore wind energy comes home	[103]	x				
Marine wind energy and the North Sea Offshore Grid Initiative: A Multi-Level Perspective on a stalled technology transition?	[46]	x				
Offshore Wind Power Integration into Future Power Systems: Overview and Trends	[28]	x				
Value of Local Offshore Renewable Resource Diversity for Network Hosting Capacity	[91]	x				
Analysis of direct interconnection technique for offshore airborne wind energy systems under normal and fault conditions	[136]	x				
Optimum sizing of offshore wind farm export cables	[137]	x				
North Sea offshore grid development: combined optimization of grid and generation investments towards 2050	[113]	x				
Large-scale integration of offshore wind into the Japanese power grid	[138]	x				
North Sea region energy system towards 2050: integrated offshore grid and sector coupling drive offshore wind power installations	[27]	x				
Techno-economic analysis of a hydraulic transmission for floating offshore wind turbines	[139]	x				
Avoidance of wind farms by harbour seals is limited to pile driving activities	[140]	x				
An offshore wind union? Diversity and convergence in European offshore wind governance	[102]	x				
Engaged minority or quiet majority? Social intentions and actions related to offshore wind energy development in the United States	[141]	x				
Dividing the sea into small bidding zones? The legal challenges of connecting offshore wind farms to multiple countries	[97]	x				

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Table B.2 (continued).

Title	Reference	Electricity Transmission	Energy Storage	Power-to-Hydrogen	System Integration	Other
Environmental impact assessment framework for offshore wind energy developments based on the marine Good Environmental Status	[31]	x				
Investigating the impact of unanticipated market and construction delays on the development of a meshed HVDC grid using dynamic transmission planning	[98]	x				
Offshore gas production infrastructure reutilization for blue energy production	[89]		x	x		
Optimizing investments in coupled offshore wind-electrolytic hydrogen storage systems in Denmark	[55]		x	x		
Offshore renewable energy exploitation strategies in remote areas by power-to-gas and power-to-liquid conversion	[142]		x	x		
A novel hybrid energy system for hydrogen production and storage in a depleted oil reservoir	[106]		x	x		
Avoidance of wind farms by harbour seals is limited to pile driving activities	[140]		x	x		
Assessment of offshore liquid hydrogen production from wind power for ship refueling	[143]		x	x		
The Impact of Process Heat on the Decarbonization Potential of Offshore Installations by Hybrid Energy Systems	[83]		x	x		
Energy utilization strategy in an offshore floating wind system with variable production of fresh water and hybrid energy storage	[144]		x	x		
Optimization-based system designs for deep offshore wind farms including power to gas technologies	[22]		x	x		
Estimating revenues from offshore wind-storage systems: The importance of advanced battery models	[110]		x			
Evaluating a new concept to integrate compressed air energy storage in spar-type floating offshore wind turbine structures	[145]		x			
A Multi-Objective Planning Framework for Coordinated Generation From Offshore Wind Farm and Battery Energy Storage System	[61]		x			
Optimization and control of offshore wind systems with energy storage	[47]		x			
Buoyant Energy-balancing wind power and other renewables in Europe's oceans	[58]		x			
A two-stage framework for the optimal design of a hybrid renewable energy system for port application	[146]		x			
A novel optimal energy management strategy for offshore wind/marine current/battery/ultracapacitor hybrid renewable energy system	[63]		x			
Seawater pumped storage systems and offshore wind parks in islands with low onshore wind potential. A fundamental case study	[147]		x			
Risk assessment of offshore wave–wind–solar-compressed air energy storage power plant through fuzzy comprehensive evaluation model	[52]		x			
Supporting the externality of intermittency in policies for renewable energy	[148]			x		
Sustainable offshore oil and gas fields development: Techno-economic feasibility analysis of wind–hydrogen–natural gas nexus	[85]			x		
Initial Design Phase and Tender Designs of a Jacket Structure Converted into a Retrofitted Offshore Wind Turbine	[149]			x		
The co-evolution of innovation systems and context: Offshore wind in Norway and the Netherlands	[104]			x		
Study on Multiobjective Modeling and Optimization of Offshore Micro Integrated Energy System considering Uncertainty of Load and Wind Power	[84]			x		
Analysis of blue energy production using natural gas infrastructure: Case study for the Northern Adriatic	[86]			x		
Dynamic analysis of an offshore monopile foundation used as heat exchanger for energy extraction	[150]			x		

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Table B.2 (continued).

Title	Reference	Electricity Transmission	Energy Storage	Power-to-Hydrogen	System Integration	Other
Offshore Power Plants Integrating a Wind Farm: Design Optimization and Techno-Economic Assessment Based on Surrogate Modeling	[151]			x		
Established sectors expediting clean technology industries? The Norwegian oil and gas sector's influence on offshore wind power	[152]			x		
Evidence for the effects of decommissioning man-made structures on marine ecosystems globally: a systematic map protocol	[153]			x		
Barrier identification and analysis framework to the development of offshore wind-to-hydrogen projects	[71]			x		
Onshore, offshore or in-turbine electrolysis? Techno-economic overview of alternative integration designs for green hydrogen production into Offshore Wind Power Hubs	[66]			x		
Optimizing hybrid offshore wind farms for cost-competitive hydrogen production in Germany	[100]			x		
Participatory design of multi-use platforms at sea	[7]					x
The role of domestic markets in international technological innovation systems	[154]					x
Balancing sustainability transitions through state-led participatory processes: The case of the dutch north sea agreement	[29]					x
REFOS: A Renewable Energy Multi-Purpose Floating Offshore System	[155]					x
Policy and Theoretical Implications of the Zero-subsidy Bids in the German Offshore Wind Tenders	[156]					x
Co-located offshore wind and tidal stream turbines: Assessment of energy yield and loading	[14]					x
Global Research and Trends in Renewable Energy: Ocean Waves, Tidal Energy and Offshore Wind	[12]					x
Planning of the installation of offshore renewable energies: A GIS approach of the Portuguese roadmap	[157]					x
Optimization of wind-marine hybrid power system configuration based on genetic algorithm	[158]					x
Goal programming models with interval coefficients for the sustainable selection of marine renewable energy projects in the UK	[159]					x
Ocean zoning for conservation, fisheries and marine renewable energy: Assessing trade-offs and co-location opportunities	[30]					x
Do people prefer offshore to onshore wind energy? The role of ownership and intended use	[160]					x
Electrifying the North Sea	[161]					x
Environmental licensing for offshore wind farms: Guidelines and policy implications for new markets	[32]					x
Generalized changes of benthic communities after construction of wind farms in the southern North Sea	[162]					x
Local voices on renewable energy projects: the performative role of the regulatory process for major offshore infrastructure in England and Wales	[101]					x
Maritime spatial planning: Germany as a forerunner in ecosystem-based management?	[163]					x
Public dialog as a collaborative planning process for offshore wind energy projects: Implications from a text analysis of a South Korean case	[164]					x
Supporting Sustainability through the Use of Offshore Wind Energy: The Case of the United Kingdom	[165]					x
The evolution of the pre- and post-construction public opinions towards offshore wind energy on the Belgian coast	[166]					x

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