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The future role of offshore renewable energy technologies in the North Sea energy system

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ABSTRACT

Offshore renewables are expected to play a significant role in achieving the ambitious emission targets set by the North Sea countries. Among other factors, energy technology costs and their cost reduction potential determine their future role in the energy system. While fixed-bottom offshore wind is well-established and competitive in this region, generation costs of other emerging offshore renewable technologies remain high. Hence, it is vital to better understand the future role of offshore renewables in the North Sea energy system and the impact of technological learning on their optimal deployments, which is not well-studied in the current literature. This study implements an improved framework of integrated energy system analysis to overcome the stated knowledge gap. The approach applies detailed spatial constraints and opportunities of energy infrastructure deployment in the North Sea and also technology cost reduction forecasts of offshore renewables. Both of these parameters are often excluded or overlooked in similar analyses, leading to overestimation of benefits and technology deployments in the energy system. Three significant conclusions are derived from this study. First, offshore wind plays a crucial role in the North Sea power sector, where deployment grows to a maximum of 498 GW by 2050 (222 GW of fixed-bottom and 276 GW of floating wind) from 100 GW in 2030, contributing up to 51% of total power generation and declining cumulative system cost of power and hydrogen system by 4.2% (approx. 40 billion EUR in cost savings), when compared with the slow learning and constrained space use case. Second, floating wind deployment is highly influenced by its cost reduction trend and ability to produce hydrogen offshore; emphasizing the importance of investing in floating wind in this decade as the region lacks commercial deployments that would stimulate its cost reduction. Also, the maximum floating wind deployment in the North Sea energy system declined by 70% (162 GW from 276 GW) when offshore hydrogen production was avoided, while fixed-bottom offshore wind deployment remains unchanged. Lastly, the role of other emerging offshore renewables remains limited in all scenarios considered, as they are expensive compared to other technology choices in the system. However, around 8 GW of emerging technologies was observed in Germany and the Netherlands when the deployment potential of fixed-bottom offshore wind became exhausted.

1. Introduction

Achieving a climate-neutral European Union (EU) by 2050 requires meeting the climate targets for 2030 and then facilitating necessary investment and policy actions to achieve the long-term targets [1]. Up till 2050, an estimated 24 billion € per year investment is required for renewable energy plants, and another 24 billion € per year investment for electricity grids to meet the targets set by the EU [2]. The UK also aims to be a net-zero GHG emitter by 2050 [3], requiring considerable investment and policy actions. As these regions attempt to drastically reduce their emissions in the coming decades, radical policy shifts and transformation of the energy system are expected.

Energy system models, commonly through optimization routines, assess future energy mix, technologies' development, investment and infrastructure needs, and deployment pathways. Based on the inputs and the targets (set as constraints), the energy system model provides an optimal cost-efficient solution, e.g., future energy generation mix, and investment needs. Our future energy system and its structure largely depend on the technologies and their cost reduction potentials, because

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Nomenclature

Abbreviations

CAPEX	Capital Expenditure
EEZ	Exclusive Economic Zone
EU	European Union
FBOW	Fixed-Bottom Offshore Wind
FLOW	Floating Offshore Wind
GB	Great Britain
GHG	Green House Gas Emissions
GIS	Geographic Information System
GW	Gigawatt
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IEA	International Energy Agency
IESA-NS	Integrated Energy System Analysis – North Sea
MGA	Modeling-to-Generate Alternatives
NIMBY	Not in my backyard
O&G	Oil and Gas
OECD	Organization for Economic Co-operation and Development
OPEX	Operational Expenditure
OWF	Offshore Wind Farm
PV	Photovoltaic
Solar PV	Solar Photovoltaic
TRL	Technology Readiness Level
UK	United Kingdom

Symbols

%	Percentage
€	Euro
km	Kilometers
L	Liters
M€	Million Euro

they provide means to achieve emission targets while compensating for necessary demand [4]. Therefore, technology cost and performance development expectations are critical inputs for energy modeling studies, emphasizing the need to better understand the technological learning process [5]. The uncertainties of the cost projections is also crucial to consider [6]. Onshore wind [7] and solar PV [8] are well-established renewable technologies in the market and their cost developments are well-studied. Both technologies are expected to play a crucial role in the future energy mix. Cherp et al. [9] stated that in the EU and other high-income OECD countries, the growth of wind and solar has stabilized mainly after an initial acceleration and concluded that the growth needs to be re-accelerated to meet the climate targets. However, permitting hurdles [10] and spatial conflicts, including social acceptance (e.g., NIMBY issues) and congestion, introduce difficulties in scaling up the onshore renewables to the desired level. Trondle [11], on the other hand, found that replacing onshore wind with offshore wind reduces land requirements drastically with minor cost penalties, thereby emphasizing the opportunities and importance of offshore renewables in achieving desired emission targets in these regions.

In the past two decades, offshore wind technology, primarily fixed-bottom offshore wind (FBOW), has progressed rapidly in Europe, mainly in the North Sea region, due to its high resource sites, shallow water depths [12]. Supportive policy conditions including Feed-in-Tariffs, contract-for-difference and grid connection subsidies also played a crucial role [13]. Along with solar PV and onshore wind, offshore wind is being discussed as a frontrunner in decarbonization plans, either via direct- or indirect electrification (synthetic fuels like hydrogen) [1,14]. Besides the role of these well-established technologies, the IEA emphasized the importance of emerging technologies by stating that almost half of the emission reductions in 2050 are expected from technologies currently in the demonstration and prototype phase [15]. IEA expects 293 GW of ocean energy[1] globally by 2050 and the EU aims to reach 1 GW of ocean energy by 2030 and 40 GW by 2050 [16]. Therefore, assessing the future role of floating wind and other key emerging ocean energy technologies, including tidal stream technology, wave technology, and biofuels from seaweed [17], is of great significance for these regions [16]. Some notable benefits these key emerging technologies can bring to the decarbonization pathways are, 1) tidal stream is predictable and is said to contribute to system balancing and reducing reserve capacity costs in the energy system [18], 2) wave energy generation complements the wind generation profile, thereby can help to diversify the production risks in the energy system [19], 3) bioethanol from seaweeds can serve as an alternative energy source for harder-to-abate sectors, including transportation and industries [20,21]. A more detailed review of these technologies and their cost-reduction potential is available in the literature [21,22]. However, a system-level understanding of their future roles in the North Sea energy system and the impact of technological learning is lacking [23].

Moreover, offshore renewables also face spatial conflicts with other marine activities, which determines the maximum available space for their deployments [24]. The North Sea, in general, is a busy area for shipping, sand extraction, Oil and Gas (O&G), fishing, and protected natural reserves. Besides, there are more than 300 O&G fields, 5000 wells, 500 platforms, and a network of around 10,000 km of pipelines in the North Sea basin. Limited interactions or synergies with stakeholders could limit the potential deployment of offshore renewables [25], emphasizing the critical role spatial constraints play in the future North Sea energy system. It is vital to quantify the future role of offshore renewables from a system-level perspective, because their deployments in the energy system are based on a multitude of factors like future demand, maximum potential, social acceptance, competing technologies, the value of energy generation in the market, availability of existing and future infrastructure (transmission and distribution); in addition to the technology cost [26] and spatial constrains which are often excluded in similar studies [27,28].

Fattahi et al. [29] conducted a broad multi-criteria analysis over an extensive literature review of 19 existing Integrated Energy System Models, highlighting the need for an improved modelling approach. He concluded that there is currently no model that simultaneously includes the following essential capabilities: hourly temporal resolution, European power dispatch, multiperiod investment optimization, complete representation of the energy system with an accounting of the GHG emissions included in the climate policy targets, complete technological representation of activities within each sector while taking into consideration (exogenous) efficiency improvements and (exogenous) technological learning, and an appropriate account of the costs of the infrastructure transformation. Further, Rafael Martinez-Gordon et al. [30] extended the literature review and emphasized the importance of spatial aspects in the energy system modelling routines as the future energy system will be dominated by highly intermittent, meteorologically and spatially dependent wind and solar technologies. The study further added that integration of higher levels of resolution of spatial data (e.g., NUTS3 level or above) is still a challenge and entails prohibitive running times. With respect to the North Sea region, the above

[1] Ocean Energy refers to marine renewable energy technologies other than offshore wind technology. This includes wave, tidal, Ocean Thermal Energy Technology (OTEC) and others. Technologies like OTEC have very low-TRL. Hence, they are not considered in this study.

discussion shows that the aspects of technological learning related to offshore renewables and spatial conflicts with existing and future marine activities plays a crucial role in assessing North Sea energy system's decarbonization pathways.

In summary, it can be seen that there is a critical gap in literature to better understand the future role of offshore renewables in the North Sea system, considering the wider system dynamics, technological learning, and spatial conflicts and opportunities. Hence, this study demonstrates an improved framework of integrated energy system analysis to address this knowledge gap, combining system analysis, spatial constraints, and technological learning. The study also assesses the impact technological learning has on the optimal deployments of offshore renewables. The first step involves estimating the maximum deployment potential of offshore renewables under two different spatial planning strategies (single- and multi-use). Then, the future role of offshore renewable energy technologies in the energy transition was quantified and the impact of technology cost on deployments was assessed under three different technological learning scenarios. The scenarios are simulated in an integrated energy system model called IESA–NS (Integrated Energy System Analysis – North Sea) [31]. IESA-NS is an hourly resolved sector-coupled integrated energy system model that overcomes the above-mentioned limitations of the exisiting models. The paper is structured as follows. First, the methodology, the energy system model, and the scenario definitions are detailed in Section 2.1. Second, the potential capacity for offshore renewables in the North Sea region and technological learning assumptions of offshore renewables are outlined in Sections 2.2 and 2.3. Third, the main results of the study are discussed. Lastly, three significant implications for policymakers, researchers, and the industry were formulated based on the outcomes of this study.

2. Methods

This study employs an improved framework involving an hourly resolved sector-coupled energy system model named Integrated Energy System Analysis for North Sea (IESA-NS) [31]. The model is used to quantify the future role of offshore renewables in the North Sea energy system and the impact of technological learning in their deployments. The approach followed in this study involves 5 major steps, as shown in Fig. 1.

1) The first step involves estimating the deployment potential of offshore renewables in the North Sea region, from both near shore and far offshore. The near shore potential for the North Sea countries was taken from literature, ENSPRESO reference scenario [32]. For far-offshore regions (>80 km from shore), the available area for deployment was estimated in this study upon excluding conflicting activities or competing claims like Natura regions, shipping routes, and O&G platforms. To assess the potential impact of these constraints on deployments, the available area of far-offshore regions was estimated under two scenarios, single-use, and multi-use spatial planning strategies. Refer to the following section for a detailed description of these two strategies. The available area in these two scenarios is further classified into two, based on water depth (less than 60 m and above 60 m for fixed-bottom and floating offshore renewables).
2) The second step involves technological cost and performance outlook for offshore renewable technologies. Both inputs for offshore renewable energy technologies were referred from literature, which used a coherent approach that enables quantifying long-term cost developments and contributing factors. The said approach leverages the merits of prevalent methods like technology diffusion curves, experience curves (multi-factor and component-based), and bottom-up cost modeling [23]. Refer [12] for fixed-bottom offshore wind, [33] for floating wind and [21] for low-TRL offshore energy technologies. To understand the potential impact of technological learning on offshore renewable deployments, the cost and performance inputs of these technologies were also defined under 3 scenarios, high-, base-, and low-learning cases. Section 2.3 provides a detailed definition of these scenarios and corresponding inputs.
3) The third step involved integrating the above-discussed spatial and technology cost outlooks as inputs into the IESA-NS model. The long-term emission targets, constraints, and policy choices were also defined in the IESA-NS model, e.g., onshore renewables maximum deployment potential, allowing offshore hydrogen production and re-use of offshore pipelines for hydrogen transportation, nuclear energy policy, and deploying shared offshore transmission infrastructure or energy islands (see [31] for full documentation).
4) The fourth step involves simulating the model to assess the decarbonization pathways under different scenarios (see Section 2.5), defined by the combinations of spatial planning and technological learning cases.
5) The last step involves interpreting the results and deriving recommendations for policymakers, industry actors, and researchers.

2.1. Energy system model and integrating spatial and technological learning inputs

IESA-NS is an open-source integrated energy system model and forms the central component of the study. The IESA-NS is a cost-optimization model that optimizes the energy system's long-term investment planning and short-term operation based on the inputs and targets provided. Detailed documentation of the model structure, and the inputs including the emission targets, demand forecasts by sectors, technology costs (excl. offshore renewables discussed in this study), and their performance assumptions can be found in [31,34]. A detailed summary of the importance of including spatial data in the energy system can be also found in [35], which includes analyzing bottlenecks in the transmission grid, assess variable renewable energy potentials, understand geographical variations of energy demand or improving routing of energy infrastructures.

The focus countries of this study are Belgium, Denmark, Germany, the Netherlands, Norway, Sweden, and Great Britain. However, the IESA-NS model includes the wider EU interconnected energy system while solving the scenarios.

Advantages of the IESA-NS model:

- Optimizes both long-term investment decisions and short-term operations
- Able to run at hourly resolution over a multi-year time span
- Allows to increase the spatial resolution of the offshore areas of the North Sea representing conflicts and opportunities for energy infrastructure
- Model includes a European representation of power and gas network (i.e., hourly dispatch of European power and daily dispatch of European Natural gas), and a complete representation of the energy system of the North Sea countries

2.2. Estimating deployment potential of offshore renewables

This section describes the approach in estimating the deployment potential of offshore renewables in the North Sea region.

2.2.1. The spatial scope of the assessment

The differentiation between nearshore areas (<80 km from shore)

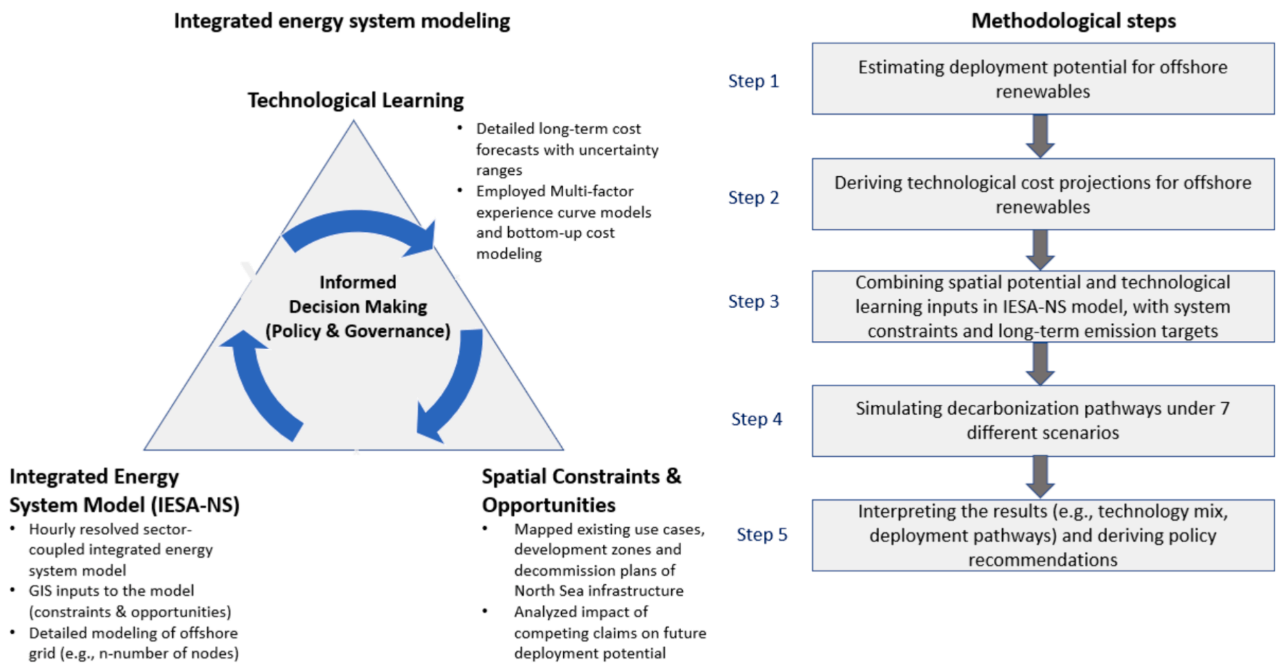

Fig. 1. Illustration of methodological framework followed in this study.

and far offshore regions (>80 km) was made to better understand the differing nature of transmission infrastructure requirements (radial vs. hub connection)[2] [14,36]. Nearshore regions are attractive for developers because of shallow water depths, closer to shore, and low grid costs (i.e., radial HVAC connections). However, these areas get crowded with increasing deployments, and then conflicts arise with other offshore activities like sand extraction, defense, fisheries, and shipping routes [37]. Hence, far offshore regions are growingly considered for future deployments and are of significant importance to the decarbonization plans. Gusatu et al. [24] analyzed the management of offshore space in the North Sea region and found that the areas close to shore offer the least possibilities for deploying offshore wind farms at scale, a maximum of 20–35 GWs. The study also concluded that areas away from 50 km and deeper water (>55 m water depth) areas pose a high potential to realize high deployment ambitions set by the North Sea countries. However, far-offshore sites will require more effective transmission systems like hub-type HVDC connections to optimize integration costs [38], as radial HVAC connections are shown to increase the total cost of offshore wind technology with distance [33].

Far-offshore regions in the North Sea area also have the potential to develop “offshore cluster regions”, where multiple offshore wind farms and energy infrastructure can be grouped, i.e., centrally connected, and the generated energy can be exported efficiently via shared infrastructure (Hub connections) [38]. The process of identifying these cluster spaces is detailed in the following section. In addition to the nearshore region (<80 km from shore), these identified offshore clusters form the spatial scope of the assessment.

2.2.2. *Identifying cluster regions in the North Sea*

A summary of integrating the spatial considerations into the IESA-NS model is provided here as a three-step process. For full documentation, refer to [39]. First, the different activities in the North Sea region are mapped in a Geographical Information System (GIS) tool using updated marine spatial plans of each country. The future developments of offshore activities (nature-protected areas, fisheries, shipping, military activities, O&G infrastructure, cables, and pipelines) were also mapped based on two spatial planning strategies, single-use, and multi-use. 1) *single-use case*, where a sectoral planning approach is followed with a limited displacement of other marine uses by offshore renewable development, 2) *multi-use case*, where a more integrated planning approach with a high level of compatibility between marine activities is considered to obtain maximum possible deployment potential for offshore renewables; see Appendix A for more details on synergy assumed with different stakeholders. This mapping exercise is done for regions beyond 80 km from shore as those are the areas of significance in the long-term development pathways of offshore renewables.

Second, the nodes, referred to as “offshore clusters”, are identified in the North Sea region by geolocating the individual offshore wind farms by their development zone’s centroids. These development zones were then clustered using the k-means algorithm.[3] The service area of each cluster is defined by extending 80 km from derived centroids of identified clusters encompassing the development zones; resulting in 6 offshore clusters in the North Sea region. Two more clusters were also added, one in the Dogger bank and one in the eastern English EEZ, as potential clusters space based on expected large-scale deployment of offshore wind farms and locational characteristics [39]; see Fig. 2. In theory, the number of clusters can be controlled to provide the extent of spatial resolution needed for a specific analysis. However, the total clusters were restricted to 8 based on an optimization assessment conducted previously [39], balancing the certainty in the results and computation effort.

Fig. 3 shows the estimated available area for offshore renewables across cluster regions identified in the far-offshore region of the North Sea, under both single-use and multi-use spatial planning strategies. These estimated areas were then converted into GW terms using

[2] Radial refers to point-to-point connection between onshore substation/landing point and offshore wind farm. Hub connection refers to grouped connection, where multiple wind farms are grouped to a single coordinated offshore point, which is then connected to the onshore substation/landing point.

[3] K-means algorithm finds natura clusters of features based on either location or attribute values. The algorithm works to classify the features of elements so that the features within a cluster are as similar as possible, while the clusters are as different as possible.

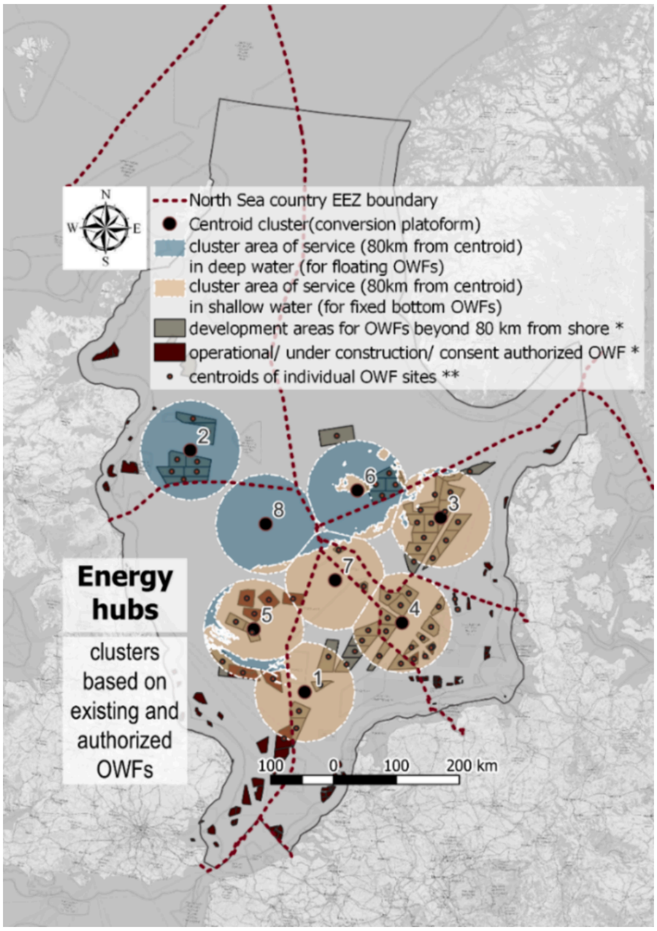

Fig. 2. Cluster regions categorized by water depth. Development areas for OWFs beyond 80 km from shore* represent the 'high certainty' OWFs (operational, under construction, consent authorized, development areas) located beyond 80 km from shore. For an equal weighting by the k-means algorithm, the input data (shapefiles) is harmonized to have similar areas by merging or dividing the OWF areas, to obtain areas approx. 600 km^2.

technology's power densities (MW/km^2); Refer to Appendix B for a summary of the results. In the IESA-NS, the cluster regions were modeled in the way where electricity generated from renewable energy technologies in each cluster is collected and transported to shore via a common HVDC export line (or via pipelines if hydrogen is produced offshore), rather than utilizing individual export lines (radial HVAC connections) which increases costs and environmental impacts [40].

2.3. Technology cost projections

This section summarizes the technology cost and performance outlook of offshore renewable technologies.

2.3.1. Technological learning

The technological learning of energy technologies is generally a complex multi-staged process [23] and the inherent characteristics of each technology play a significant role in defining the extent of their cost reduction through upscaling and learning by doing [41]. Modular technologies achieve product standardization faster. Hence, their cost reductions are mainly driven by learning by doing, e.g., solar PV. On the other hand, technologies like wind turbines upscale initially and achieve cost reduction through scaling, before learning by doing becomes prevalent [42]. A better understanding of these characteristics and cost reduction drivers is crucial in quantifying the future costs of technologies with certainty, as simple extrapolations of technology costs were found to differ considerably from observed costs [43].

Offshore wind, both fixed-bottom and floating variants, is a complex large-scale energy technology. CAPEX,[4] OPEX[5], and performance (function of capacity factor), are impacted by varying site characteristics and economic parameters [44]. Tidal stream and wave technology are also considered complex energy technologies due to the similarities in operating environments and characteristics. However, wave energy technology designs show modular characteristics [21,45] like solar PV and battery, than offshore wind and tidal stream technologies. As explained above, these inherent characteristics play a critical role in determining the pace and extent of cost reduction. Santhakumar et al. [23] proposed a coherent framework, which enables understanding such differences in developments and forecast technology costs in a detailed manner. The said framework leverages prevalently used methods including experience curve (multi-factor and component-based), bottom-up cost modeling, and technology diffusion curves to overcome the limitations posed by individual approaches. By applying this framework, long-term cost assessments were derived for offshore renewable energy technologies, i.e., offshore wind [33,46], wave, tidal stream, and bioethanol from seaweed [21]. These projections are available based on the cumulative output of the technology (GWs installed or GWh energy generated) and not time. Therefore, these inputs were converted into time-based cost projections to conform with IESA-NS model requirements. For this conversion, market deployment growth curves for offshore technologies were used. The derivation of such curves is explained as follows. For fixed-bottom, a compound annual growth rate (CAGR) of 18 % was estimated from the deployment data available in the literature until 2030 [47]. The deployment up to 2050 was then projected using this estimated CAGR for the base-learning case. For high- and low-learning cases, 21 % and 12 % were applied; refer to [33] for more details. For floating wind and other Low-TRL technologies, the market deployment growth was modeled using diffusion curves (s-curve, sigmoid function). The growth rates used for low-, base- and high-learning cases are 0.2, 0.3, and 0.4. Similar growth rates (low, average, and high) were observed for electricity supply technologies in the market; refer to [48] for more details.

Table 1 provides the cost and performance range for offshore wind, tidal stream, and wave technology applied in this study. The extremes of the range refer to 'High learning' and 'Low learning', i.e., lower costs and higher performance factor refers to the high-learning case. 'High learning' refers to rapid cost reduction through accelerated deployment, innovation, and strong policy support. 'Low learning' refers to delayed cost reduction through ineffective policy and investment actions, e.g., a wait-and-see approach to investment decisions, not streamlining permitting procedures, and NIMBY-type responses. The third case, named 'Base-learning', refers to average cost reduction through business-as-usual developments with the same policy support and deployment rate as today (inputs are summarized in Appendix C).

2.3.2. Bioethanol from seaweed

Unlike electricity generation technologies discussed above, bioethanol production from seaweed involves a value chain of processes from offshore feedstock cultivation, transportation of feedstocks to the shore, and then biochemical conversion to ethanol. Similar to the technologies discussed above, the cost inputs are the results of detailed long-term cost assessments published in the literature [21]. The

[4] The CAPEX for the technologies are derived by leveraging the merits of bottom-up engineering cost modeling and experience curve approach. Bottom-up cost modeling was used to derive the initial CAPEX estimate and the cost drivers. The long-term estimates are derived by apply an experience cuve approach, based on cumulative installed capacity.

[5] CAPEX refers to the capital expenditure, comprising the total of component costs. OPEX refers to all-in-costs required to maintain the operations of the power plant through its lifetime.

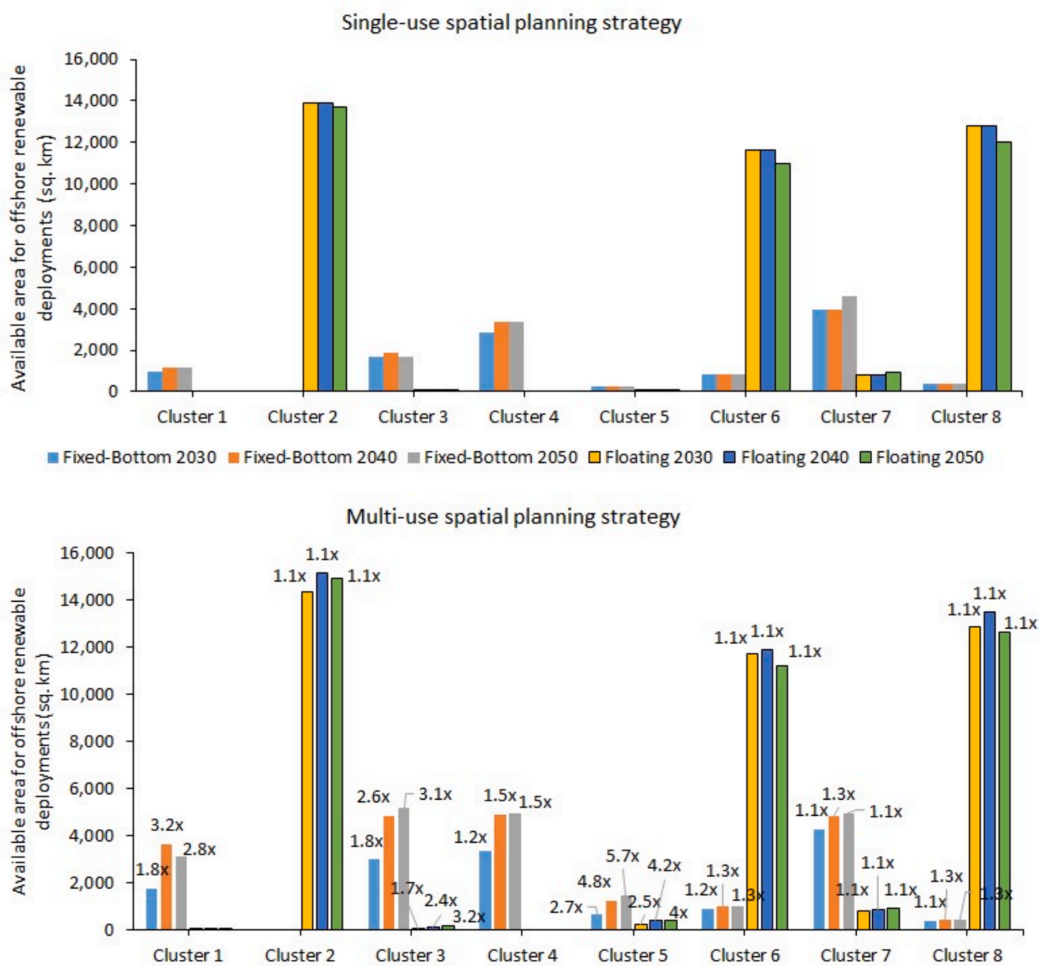

Fig. 3. Illustration of estimated available area for offshore renewables across clusters under single-use and multi-use spatial planning strategy. The increase in available area in the multi-use case, compared to the single-use case, is indicated as data labels in the graph (e.g., 1.5x meaning the multi-use case has 50% more area than the single-use case).

bioethanol cost inputs applied in the IESA-NS model are summarized in Table 2. In 2022, bioethanol cost in Europe stands at 1.1 – 1.3 €/L [49], indicating the price gap the emerging technology poses in the market. It should be also noted that the IESA-NS model also includes competing carbon–neutral fuel choices, including biofuels from 1st or 2nd generation biomass feedstocks, and the import of bioethanols, and the deployment will be influenced by the competitiveness of the technology in the market.

The third step of the process involves integrating the technological learning and spatial potential of offshore deployments discussed above as inputs in the IESA-NS model.

2.4. Defining scenarios

The fourth step of the method followed in this study is defining scenarios. Technological learning and spatial constraints are two significant factors that influence the deployment of offshore renewable technologies in the North Sea energy system; see Section 2.1. Therefore, their impact on the role of offshore renewable in the North Sea is quantified by deriving scenarios based on these two factors. Technological learning scenarios, high-, base- and low-learning cases, represent the pace of the cost reduction of technology and also influence how competitive they are in comparison with existing technologies in the market. Base-learning refers to the business-as-usual case for cost reduction for offshore renewables. High-learning refers to the accelerated cost reduction, while low-learning refers to delayed cost reduction for offshore renewables. The pace of the cost reduction have significance on their deployments, as noted in Section 1. Further, spatial constraints scenarios, single- and multi-use spatial planning cases, represent the maximum available deployment potential for a technology. Single-use restricts synergies between marine use cases. Multi-use spatial planning, on the other hand, maximizes the deployment potential of offshore renewables by utilizing the synergies available across different marine activities. It is crucial to quantify the impact of spatial constraint and trade-offs in deployment choices because a technology could be competitive in the system but the spatial constraint imposed could not allow its deployment, which will force a decision to consider other technology options to meet the demand in the system. Understanding such trade-offs and the reason behind them is crucial for long-term policy making, e.g., lessons for marine spatial planning. Therefore, by combining the spatial and technological learning factors, 6 scenarios were derived as shown in Table 3. In each scenario, a technological learning case and spatial planning strategy is combined to understand the dynamics and trade-offs in technology choices. Lastly, it is evident that low-TRL offshore renewables pose high costs today, and it would help decision-makers if they can understand the cost levels at which they enter the technology mix and contribute to the system. So, public investments for those technologies can be evaluated. Therefore, the "Off_Entry_snigle-use" case was derived as a 7th Scenario, which is applied to better understand the competitiveness of low-TRL offshore renewable energy technologies (tidal stream, wave, and bioethanol from seaweed) in the North Sea energy system. The results and conclusions

Table 1
Cost and performance improvements estimates applied for offshore renewable energy technologies (electricity generation). The range describes the value between the low and high learning cases.

Parameter	Units	Technology	2030	2040	2050
CAPEX	$M€/MW$	Fixed-Bottom	2.02–1.65	1.97–1.65	1.95–1.65
		Floating	3.56–2.97	3.08–2.14	2.85–1.96
		Tidal-Stream	5.31–4.18	4.57–2.41	4.10–1.92
		Wave Technology	6.33–5.97	4.92–2.41	4.14–1.86
OPEX	$K€$ per MW per year	Fixed-Bottom	47.5–40	42.5–30	37.5–30
		Floating	62.5–55	57.5–40	52.5–35
		Tidal-Stream	180–140	150–90	100–65
		Wave Technology	140–120	100–85	75–55
Capacity Factor	%	Fixed-Bottom	47.5–55	52.5–60	55–60
		Floating	45–50	50–60	55–60
		Tidal-Stream	37.5–40	40–45	40–45
		Wave Technology	27.5–30	32.5–45	40–45
Lifetime	Years	Fixed-Bottom	25–30	25–35	25–35
		Floating	25–30	25–35	25–35
		Tidal-Stream	20–25	20–35	20–35
		Wave Technology	20–25	20–30	20–30

Table 2
Summary of bioethanol cost from seaweed under different learning scenarios.

Year	Bioethanol Cost €/L		
	Low Case	Base Case	High Learning
2030	10.2	7.3	4.2
2040	5.3	3.4	1.4
2050	4.1	2.0	0.8

from the model are discussed in the following sections.

3. Results and Discussion

In this section, the deployment dynamics of offshore renewables, their contribution to the electricity and hydrogen generation in the North Sea, and also their role in wider North Sea energy system is discussed.

3.1. Offshore wind deployments in the North Sea region and regional dynamics

Fig. 4 (A) illustrates the observed ranges in total deployments for fixed-bottom and floating wind in the North Sea region across all scenarios considered in Table 3. Fixed-bottom offshore wind deployment grows from 99 GW in 2030 to a maximum of 222 GW in 2050, reaching 100 % of the total deployment potential available from the near-shore region and far-offshore clusters in all scenarios considered. Floating wind deployment grows from 1 GW in 2030 to a maximum of 276 GW in 2050, reaching 92 % of the deployment potential available from near-shore regions and far-offshore clusters in the most optimistic scenario considered (High_Lrn_multi-use). It can be observed from the supply curves (Fig. 4 (B)) that fixed-bottom offshore wind technology is already well-established and competitive in the North Sea region. Hence, its deployments were not highly influenced by its cost reduction. Floating

Table 3
Summary of scenarios analyzed in this study, their definitions, and inputs considered. The technology cost inputs for base-, low- and high-learning cases are made available in Appendix C and Table 1. The available spatial potential for both single- and multi-use spatial planning strategies are shown in Fig. 3.

Scenario	Technology cost assumptions	Spatial planning strategy	Comments
Base_Lrn_single-use	Base case learning, meaning average cost and performance developments	Single-use spatial planning	The case where business-as-usual is followed for both cost developments and spatial planning. No synergies with other marine stakeholders are realized to improve area availability for offshore technology deployments.
High_Lrn_single-use	High learning assumptions and increased deployments	Single-use spatial planning	The case consideres optimistic or accelerated cost reduction but spatial planning policies are same as today
Low_Lrn_single-use	Low learning assumptions and delayed deployments	Single-use spatial planning	Most pessimistic scenario amongst all considered, with delayed cost reduction and restrictive spatial planning policies.
Base_Lrn_multi-use	Base case learning, meaning average cost and performance developments	Multi-use spatial planning	Business-as-usual developments for cost reduction, but the spatial planning strategies are relaxed, involving synergies with other marine stakeholders
High_Lrn_multi-use	High learning assumptions and increased deployments	Multi-use spatial planning	Most optimistic scenario amongst all considered. Accelerated cost reduction and relaxed spatial planning strategies
Low_Lrn_multi-use	Low learning assumptions and delayed deployments	Multi-use spatial planning	Spatial planning strategies are relaxed but the cost reduction is delayed
Off_Entry_single-use	High learning assumptions for the tidal stream, wave, and bioethanol from seaweed. Base case assumptions for fixed-bottom and floating offshore wind.	Single-use spatial planning	Scenario to test the conditions when the low-TRL technologies enter the energy mix, i.e.,to understand their competitiveness and subsidy level needed

wind, on the other hand, is an emerging technology and its deployments are significantly influenced by its cost reduction, i.e., reaching up to 276 GWs at 32 EUR/MWh level, from 1.4 GWs at 52 EUR/MWh.

Table 4 below summarizes the total deployments of offshore wind in GWs under different scenarios in the North Sea region and the share of nearshore deployments. It can be seen that close to half of the fixed-bottom offshore wind deployments are in the nearshore regions in the single-use spatial planning case. In the multi-use spatial planning case, the near-shore deployments don't change in absolute terms (GWs), although the proportion declines due to increased deployments made in the far-offshore clusters; showing that near-shore regions are preferred first due to the low integration costs. Similarly, for floating wind, deployment in the early periods (2030) was heavily concentrated in the near-shore regions due to their low integration cost. However, as cost declines, the expansion of the deployment happens in both near-shore

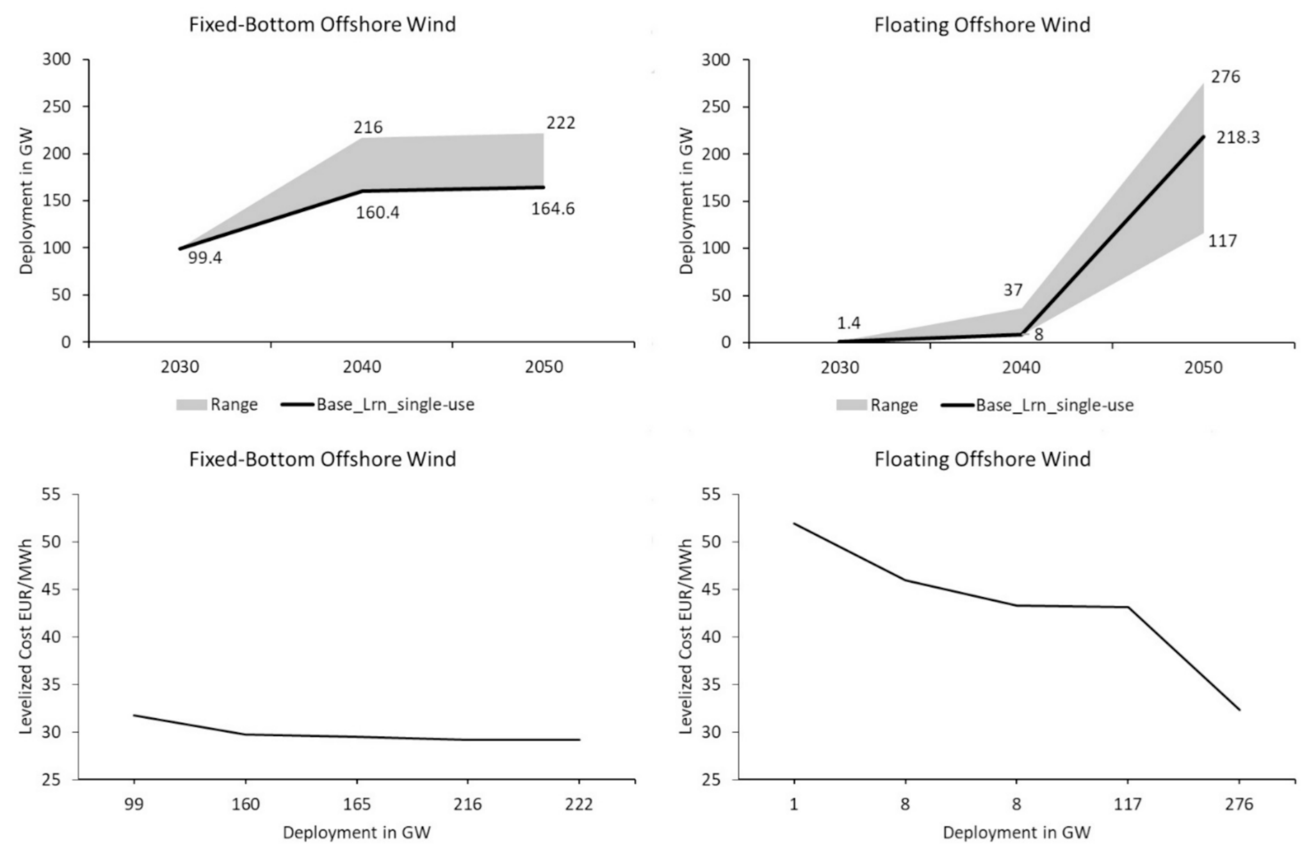

Fig. 4. A) Total offshore wind deployments in the North Sea region. The range describes the upper and lower limit corresponding to all the scenarios considered in this study. B) Illustration of the deployments observed across all scenarios as technology supply curves.

Table 4
Summary of offshore wind deployments under different scenarios and proportion of nearshore offshore wind capacity in total deployments (shown in brackets).

	Fixed-bottom offshore wind - GW			Floating offshore wind - GW		
	2030	2040	2050	2030	2040	2050
Base_Lrn_single-use	99 (49 %)	160 (44 %)	165 (43 %)	1 (100 %)	8 (100 %)	218 (18 %)
High_Lrn_single-use	99 (49 %)	160 (44 %)	165 (43 %)	1 (100 %)	8 (100 %)	131 (31 %)
Low_Lrn_single-use	99 (49 %)	160 (44 %)	165 (43 %)	1 (100 %)	37 (22 %)	259 (15 %)
Base_Lrn_multi-use	99 (49 %)	216 (33 %)	222 (32 %)	1 (100 %)	8 (100 %)	194 (21 %)
High_Lrn_multi-use	99 (49 %)	216 (33 %)	222 (32 %)	1 (100 %)	8 (100 %)	117 (34 %)
Low_Lrn_multi-use	99 (49 %)	216 (33 %)	222 (32 %)	1 (100 %)	17 (50 %)	276 (14 %)

and far-offshore regions in the years 2040 and 2050.

Before discussing the regional deployment dynamics of offshore wind, the role of other emerging offshore renewables is discussed. Deployments for tidal-stream and wave technology were found in High_Lrn_Single-use and High_Lrn_Multi-use cases in the year 2050 alone (Fig. 5). In other scenarios, these technologies didn't enter the system, i.e., less competitive compared to other offshore wind and onshore technologies. In the High_Lrn_Single-use case, 0.4 GW of the tidal stream was deployed, which represents only about 2 % of the total deployment potential (Appendix B). In the same scenario, 8 GW of wave technology was deployed, representing 43 % of the total deployment potential (Appendix B). In the multi-use case, the deployment of the tidal stream remains unchanged. However, the deployment of wave technology reduced to 2 GW from 8 GW in the single-use case while offshore wind deployment increased, indicating a trade-off between technology deployment choices based on costs and available deployment potential. Moreover, the bioethanol from seaweed only enters the supply mix in the High_Lrn scenarios, where the cost per liter is competitive with the market price (Table 2). The role of these emerging technologies is further discussed in section 3.4.

3.1.1. *Regional dynamics in fixed-bottom offshore wind deployments*

Fig. 6 shows fixed-bottom offshore wind deployments at the country level in *Base_Lrn_single-use* and the change (+/-) in GW deployments for all other cases with the outcomes of *Base_Lrn_single-use*. In the base scenario (Base_Lrn_single-use), the top three countries with the highest deployments in the North Sea region are Great Britain, the Netherlands, and Germany with 51, 43, and 31 GW by 2050 respectively. Denmark and Norway follow the rank with 16 and 8 GW by 2050, totaling 165 GW. In low-learning and high-learning cases, the deployments didn't differ, meaning delayed or accelerated cost reduction didn't impact the deployments of fixed-bottom offshore wind technology, as discussed in the previous section.

When a multi-use spatial planning strategy is considered, the deployments increased notably for Denmark, the Netherlands, Great Britain, and Germany. Denmark saw the highest increase in deployments of about 20 and 22 GW in 2040 and 2050 respectively. It can be summarized from this section that technological learning didn't impact the deployment of fixed-bottom offshore wind significantly compared to the spatial planning strategies.

3.1.2. *Regional deployments in floating offshore wind*

Fig. 7 shows the floating wind deployments by country in

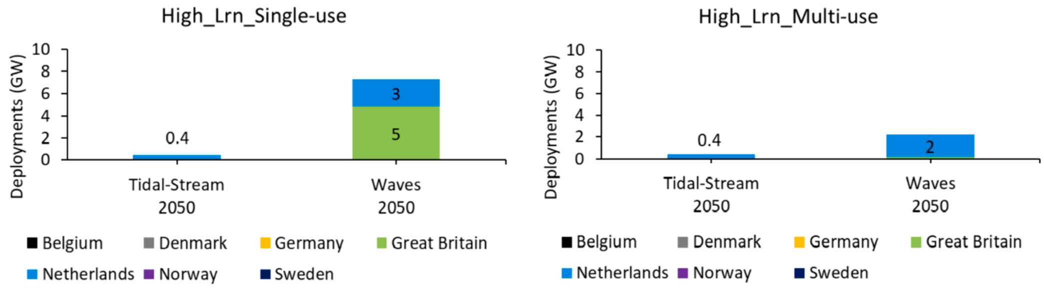

Fig. 5. Low-TRL technology deployments in High_Lrn_Single-use scenario in the Year 2050. In other scenarios, no deployments were observed for tidal-stream and wave technology.

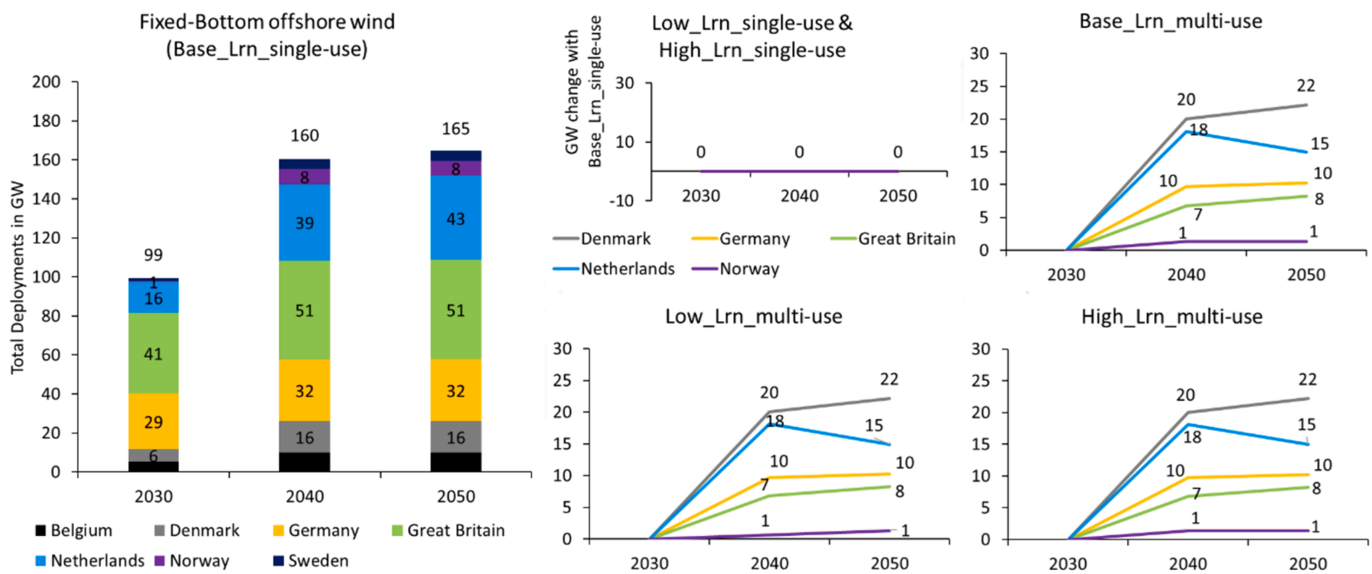

Fig. 6. Fixed-bottom offshore wind deployments by countries in the North Sea region and change in deployments under different scenarios.

Base_Lrn_single-use and the change in GW deployments across other scenarios. In *Base_Lrn_single-use*, three countries namely Great Britain, Norway, and the Netherlands show deployments of about 183, 29, and 6 GW by 2050. Contrary to fixed-bottom offshore wind, learning significantly influences deployments of floating wind, as it is an emerging technology and is currently expensive (Table 1). In *Low_Lrn_single-use*, the deployments in Great Britain decreased by 58 GW in 2050 due to delayed learning. In *High_Lrn_single-use*, the deployments in Great Britain increased by 23 GW in 2040, while the 2050 value remained the same; indicating earlier adoption due to lower technology costs. In the same scenario case, the floating wind deployments in Norway increased by 41 GW in 2050, and in the Netherlands by 5 GW in 2040.

In the multi-use spatial planning strategy, the deployments in Great Britain decreased by 4 GW in 2050 in the base learning case and by 15 GW in 2050 in the low learning case; offset by increased fixed-bottom offshore wind deployments in the multi-use spatial planning strategy (Fig. 6). In summary, floating wind deployments are largely influenced by technological learning. When spatial planning strategies are considered, a differing effect was observed where the floating wind deployments were offset by a cost-competitive option, fixed-bottom offshore wind, in the multi-use spatial case.

3.2. *Role of emerging offshore renewable technologies in the energy system*

As discussed in Section 3.1, the role of the tidal stream and wave was very limited in the six scenarios considered. Nevertheless, it is crucial to understand the competitiveness of these technologies. Therefore, the *Off_Entry_Single-use* scenario case was developed (Table 3), where the base case learning conditions for fixed-bottom and floating wind were used together with high learning conditions for the tidal stream, wave, and bioethanol from seaweed; assuming accelerated uptake of these technologies through innovation. Fig. 8 shows the resulting deployments where 8.2 GW of wave and 0.4 GW of tidal stream capacity were deployed in total. Despite the accelerated learning assumption, no material improvements in deployments were found for these technologies compared to the previously discussed High_Lrn_single-use case (Fig. 5), i.e., only a 0.2 GW increase in wave technology deployment was observed. The case is similar for bioethanol supply from seaweed.

To understand the cause of such low deployments, the LCOE of these technologies were compared (Fig. 9). It can be seen that fixed-bottom offshore remains the most cost-competitive option, evident from reaching 100 % deployment potential irrespective of the learning assumption (see Section 3.1). The second most competitive option is seen to be floating wind, also evident from increasing deployments with accelerated learning. Both tidal stream and wave seem expensive options for deployments of all four electricity generation technologies. It should be noted here that the deployments of these low-TRL offshore renewables in the clusters of Germany, Great Britain, and the Netherlands (Fig. 8) were only forced due to the following two reasons, 1) the deployment potential of fixed-bottom offshore wind was exhausted in the relevant clusters (Appendix B), and 2) the deployment potential of floating wind, the second most cost-competitive option, was also limited due to the shallow water depths in the relevant clusters. Hence, the next available technologies, wave, and tidal stream, were chosen for deployments in those clusters. This observation also shows

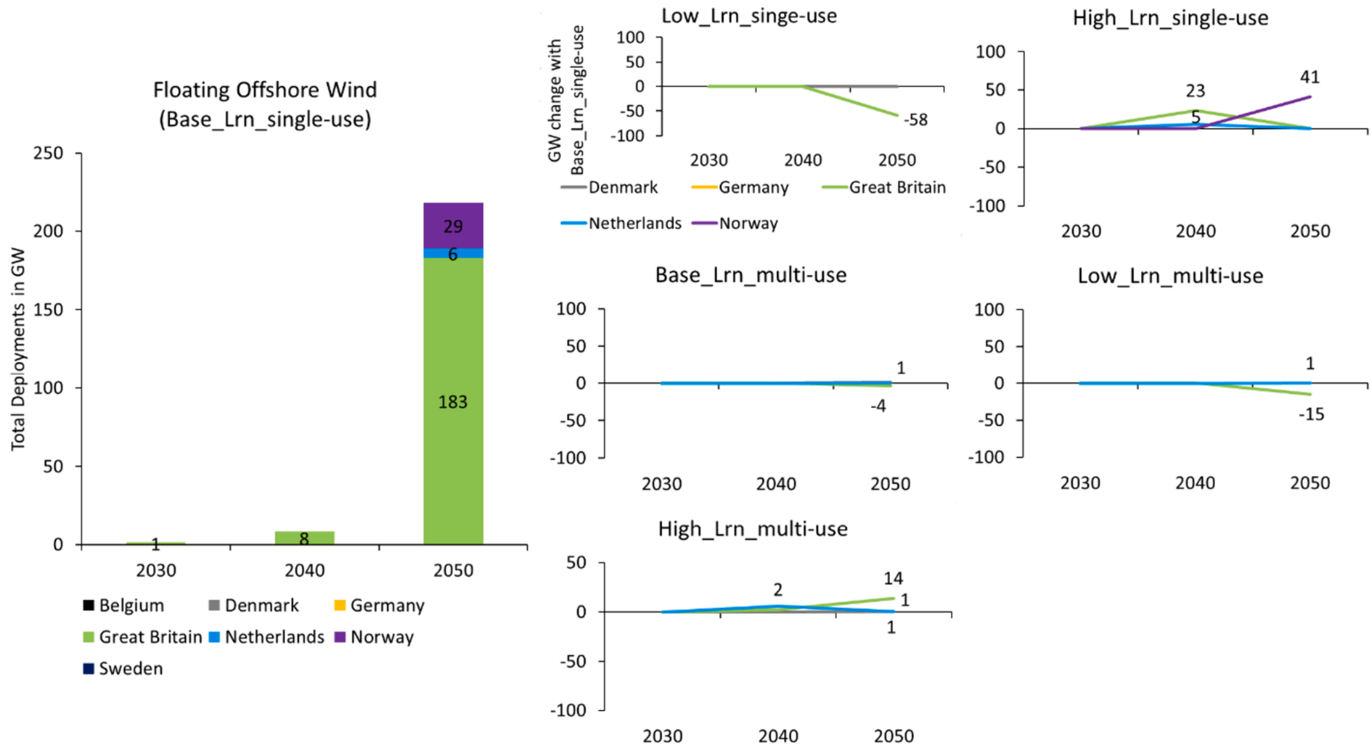

Fig. 7. Floating wind deployments in the North Sea countries and change in deployments under different scenarios.

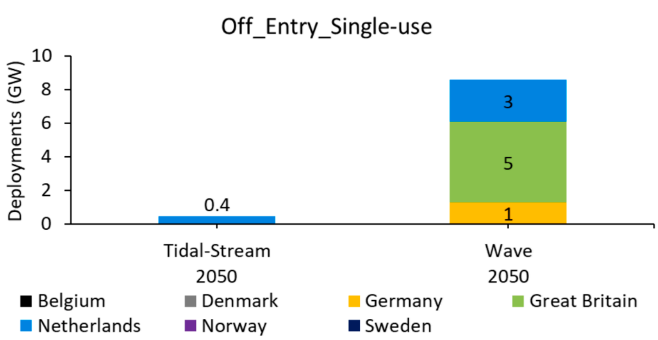

Fig. 8. Tidal stream and wave energy technology deployments in Off_Entry_Single-use case in the year 2050.

that if future spatial policies become restrictive for fixed-bottom offshore wind due to conflicts with other marine activities, policy-makers can consider stimulating the deployment of these low-TRL technologies, provided the cost of resolving those conflicts is higher than the generation cost gap between these technologies.

3.3. *Offshore renewables contribution between the electricity and hydrogen generation*

The discussion in the above sections shows that accelerated cost reductions and relaxed spatial planning strategies can significantly increase the deployments of offshore wind in the North Sea energy system. However, a significant degree of curtailment can be expected during high wind and low demand periods, limiting the value of the offshore wind in the energy system, and thereby reducing its deployment. To avoid such cases, hydrogen production from offshore wind was commonly explored as an effective integration route, as the generated

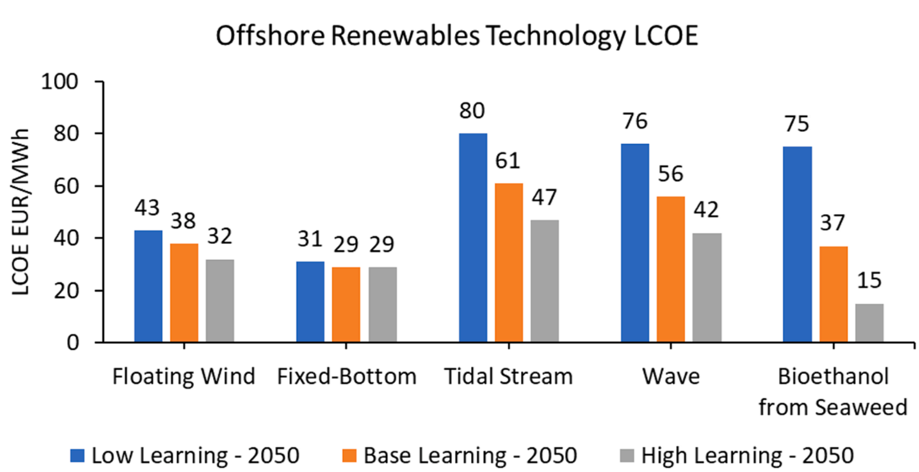

Fig. 9. Estimated LCOE of offshore renewable technologies in the year 2050 in EUR/MWh.

hydrogen can be transported onshore to facilitate the decarbonization of harder-to-abate sectors like industries. Moreover, higher capacity factors, centralized structure, and scale of the technology make offshore wind an attractive power source for hydrogen production. Therefore, here, how the energy generated from offshore wind is transported to the onshore grid (electricity via transmission cables or hydrogen via retrofitted/new subsea gas pipelines) is discussed to better understand whether offshore hydrogen production facilitates further deployments of offshore wind in the system. This analysis is made by assessing the offshore infrastructure deployed in the year 2050 of the Base_Lrn_Single-use case (representing the business usual case) and the High_Lrn_Multi-use case (most optimistic scenario), and then, their deployment trends were compared with a scenario case where offshore hydrogen production was not allowed.

Figs. 10 and 11 show the deployed infrastructure in the far-offshore clusters in the Base_Lrn_single-use and High_Lrn_multi-use cases. The figures also illustrate the proportion of the landed energy in the respective region in the form of hydrogen or electricity. Before discussing the landed form of offshore wind generation in each country, the locational choice of deploying electrolyzers for hydrogen should be noted in both scenarios, i.e., majorly concentrated in clusters 2, 8, and 6, the northern part of the North Sea where floating wind deployment is suitable. Here, a new scenario where offshore hydrogen production was not allowed was applied. Upon comparing the outcomes, it was observed that the floating wind deployments decreased by 70 % when offshore hydrogen production wasn't allowed (162 GW from 276 GW), while the fixed-bottom offshore wind deployments didn't change. This clearly shows how offshore hydrogen production will maximize the value and facilitate the maximum deployment of floating offshore wind technology in the North Sea energy system.

Moreover, in Great Britain, Germany, and Denmark, a significant portion of the landed offshore wind generation remains in the form of electricity in the Base_Lrn_single-use case. In the High_Lrn_multi-use case, the contribution of hydrogen in the landed offshore generation increased in Great Britain and Germany. In the Netherlands, more than 50 % of the landed offshore wind energy is in the form of hydrogen in both cases. It should be noted that offshore hydrogen production is limited in the clusters located closer to the Netherlands. The hydrogen generated in the Northern part of the North Sea, where the floating wind was deployed, was transported to the Netherlands via existing and newly built pipelines; emphasizing the need for an integrated offshore grid that would facilitate active hydrogen and electricity trade in the North Sea region.

3.4. Role of offshore renewables in the North Sea power generation

In previous sections, the deployment trends of offshore renewable energy technologies and their regional dynamics were discussed. Here, the broader role or contribution of offshore wind and other low-TRL technologies in the whole North Sea energy system is discussed. Fig. 12 (A) shows the technology mix in the North Sea power system and the cumulative system cost of electricity and hydrogen system of the North Sea countries across different scenarios considered in this study. The figure shows that the contribution of offshore wind technology to the North Sea power system is significant, e.g., offshore wind contributes to a maximum of 51 % of total power generation in the North Sea energy system. Moreover, offshore wind contribution to the power system is influenced by both technological learning and spatial planning strategies; although more by the former based on the discussion in previous sections. The impact of technological learning of offshore renewables is two-fold, one on the contribution of offshore wind to the total power generation and the other on the cumulative system costs of electricity and hydrogen systems. First, the share of offshore wind generation increases with accelerated cost reduction, growing from 32 % of total generation in the Low-Lrn-Single-use case to 51 % in the High_Lrn_Multi-use case. Second, the cumulative system costs of electricity and heating systems of the North Sea countries throughout its transition period declined to a maximum of 4.21 % in the High_Lrn_Multi-use case while offshore hydrogen production increased (Fig. 11), amounting to approx. 40 billion EUR, compared to the Low-Lrn-Single-use case. As fixed-bottom and floating wind deployments increase and expand to global markets like Asia-pacific and North America, the learning system for the technology will become global which in turn will reinforce the accelerated cost reduction trajectory for offshore wind technology (both

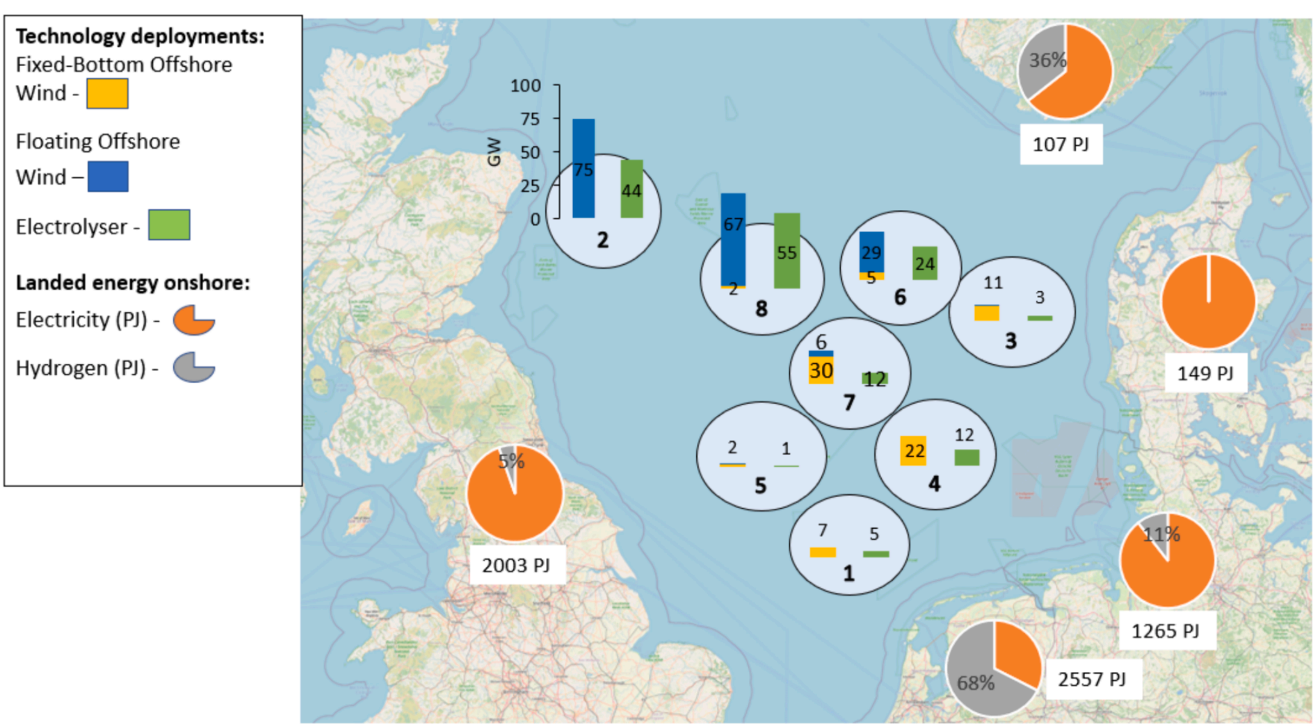

Fig. 10. Offshore infrastructure of the North Sea region in the Year 2050 at Base_Lrn_Single-use case.

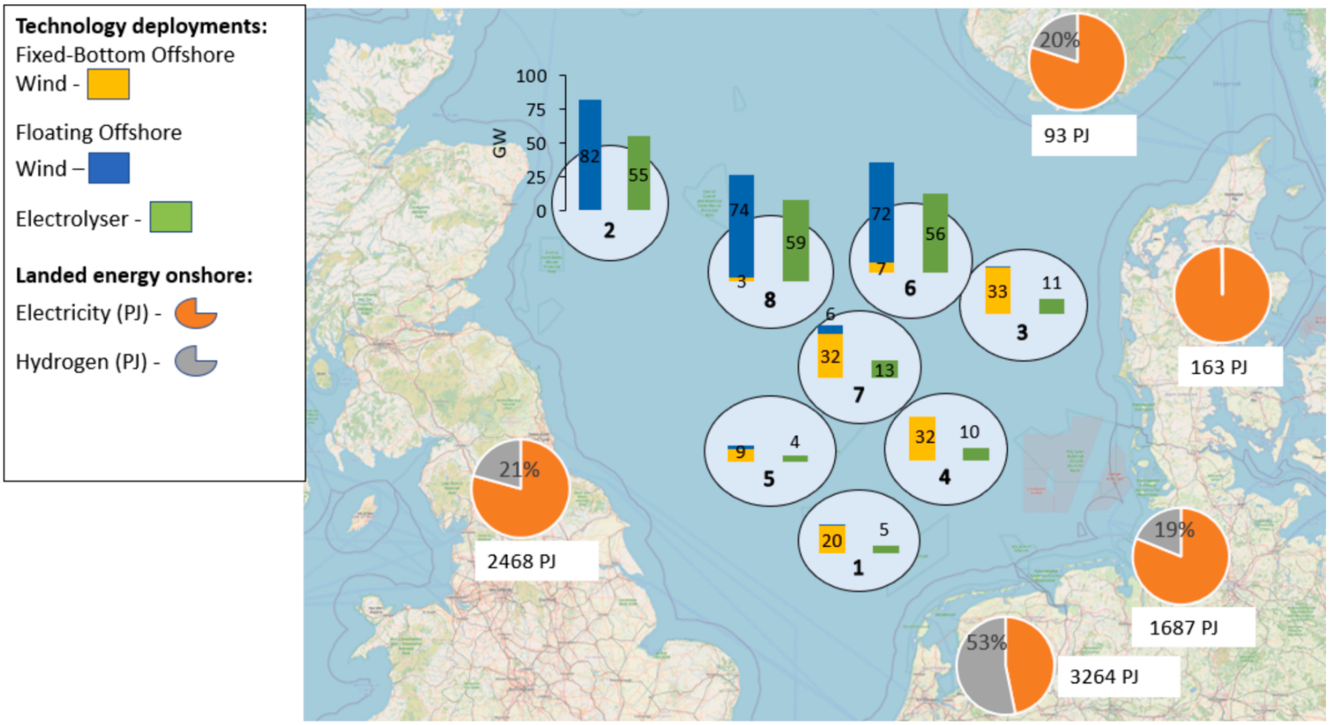

Fig. 11. Offshore infrastructure of the North Sea region in the Year 2050 at High_Lrn_Multi-use case.

fixed-bottom and floating); indicating the potential of realizing these benefits in the North Sea energy system via supporting accelerated cost reduction of offshore wind.

Next, the impact of spatial planning strategies on offshore deployments. Multi-use spatial planning strategy generally increases the available space for offshore renewable deployments. However, the deployment of a specific technology depends on its competitiveness in the market and not just on its availability. Fixed-bottom offshore wind technology is less capital-intensive compared to floating wind; see Table 1. Therefore, in the multi-use spatial planning cases where the deployment potential expands across technologies (Fig. 3), the model opts for less expensive fixed-bottom offshore wind technology over the floating wind or other low-TRL offshore renewables, i.e., fixed-bottom deployment has increased in all scenarios of multi-use cases, compared to single-use case (Fig. 4(B)). Proportionally, the effect can be also seen in the power generation mix (Fig. 4 (A), where the contribution of fixed-bottom offshore wind in power generation increased by 4–6 % more in all multi-use cases while floating wind contribution declined or remained the same. Besides, the displacing of onshore renewables by offshore wind in power generation can also be seen in cases of high learning; Fig. 4 (A).

3.5. Uncertainties involved

In this section, three major uncertainties involved that can alter the stated results are discussed. First, uncertainty in the cost reduction inputs of offshore renewables and its impact on deployment trends. As mentioned in Section 2.3, the experience curve cost projections are converted into time-based inputs for the IESA-NS (bottom-up integrated energy system model) by assuming the deployment growth of offshore renewables. Although fixed-bottom offshore wind is well-established in the region, floating wind and other Low-TRL technologies are yet to have a fully operational large-scale commercial plant in place in the North Sea region. Therefore, their deployment uptake in the North Sea region can vary depending on the policy and market conditions and developments, which in turn will alter the cost projections of the technologies and their competitiveness in the market. With significant deployments observed for floating wind across the scenarios considered, changes (e.g., delays) in its cost reduction will be highly influential toward its deployment outcomes.

Second, this study observed that fixed-bottom offshore wind achieved 100 % of its deployment potential irrespective of the learning scenario (Section 3.1). In such cases, the spatial planning assumptions that lead to the maximum deployment potential of a technology are significant. Nature-protected areas and fisheries are two main activities that pose a larger overlap with offshore renewable infrastructures (refer to Appendix A for more details). In the multi-use spatial planning case, it was assumed that synergies with other marine stakeholders and deployment of offshore renewables can be maximized, e.g., 10 % of the currently designated and future nature-protected areas are made available for offshore renewable deployment in the year 2050 (refer to Appendix B for more details on this estimation based on deployment targets). However, future developments in spatial planning can become more restrictive or more relaxed than expected here and it can influence the final technology mix of the North Sea energy system. Hence, the deployment range provided between single-use and multi-use should be considered when assessing the results (Fig. 4).

Lastly, Section 3.3 shows that offshore hydrogen production enables a 70 % increase in floating wind deployments in the North Sea region. In IESA-NS, the activities and demand across the entire European region are considered while deriving North Sea transition pathways. However, as the global hydrogen market and broad energy market develop, there are uncertainties to consider where regions including the Middle East and Asia Pacific, can produce and ship hydrogen competitively compared to the North Sea countries; similar to Liquefied Natural gas. In such cases, hydrogen imports will increase, which in turn can reduce the value of floating wind in the North Sea energy system and slow down its deployment in the region. On the contrary, it can be also expected that higher interconnection capacities across the European region (current EU targets stand at 15 % of installed capacity by 2030) can absorb high levels of offshore wind to the onshore grid. Besides, there is also uncertainties in development of hydrogen production equipment cost, including technological learning transfer between markets similar to solar PV and battery supply chain. Therefore, it should be noted that

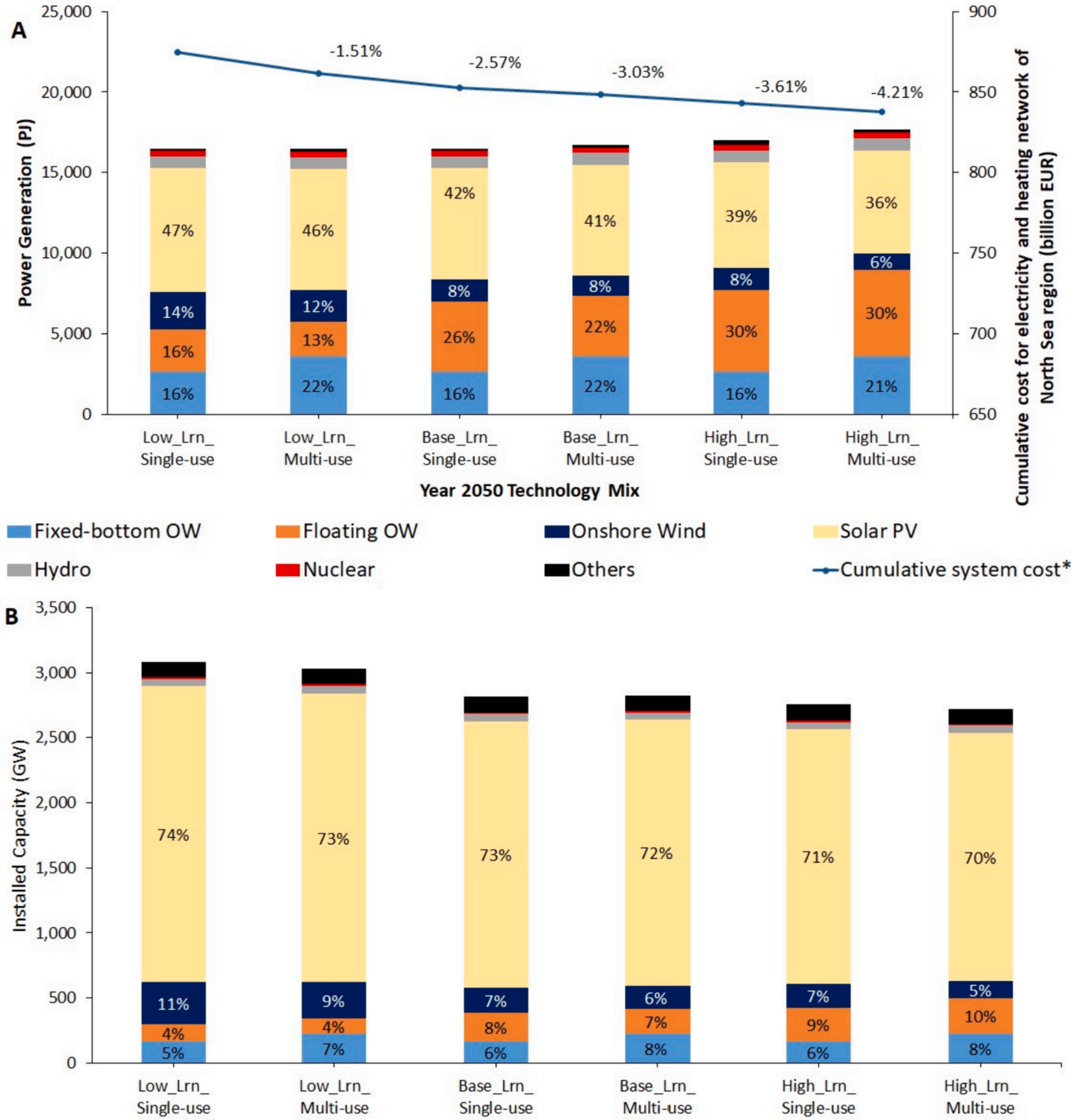

Fig. 12. A) Illustration of the power generation mix and the cumulative system cost of the electricity and hydrogen system(This cost refers to the total amount spend on investment, operation and decommission (if applicable) of power generation and hydrogen system of the North Sea countries throught its transition period. The impact of technological learning of offshore renewables is quantified by comparing this cumulative system cost across different scenarios.) of the North Sea countries throughout its transition period. North Sea countries include Belgium, Denmark, Germany, the Netherlands, Norway, Sweden, and Great Britain. 'Others' refers to all other technologies including the emerging offshore renewables such as wave energy and tidal-stream technology. B) Illustration of deployment of technologies in the North Sea energy system in the year 2050 and across different scenarios.

such regional and global energy market developments can have implications for technology deployments in the North Sea region, not just its cost reduction alone albeit being a vital factor.

4. Conclusions

This study demonstrates an improved framework of integrated energy system analysis, combining system analysis, spatial constraints, and technological learning, and then quantifies the future role of offshore renewables in the North Sea energy system. The study also assesses the impact technological learning has on the deployments of offshore renewables. Based on the assessment, five major conclusions and recommendations are summarized here for the offshore renewable industry, policymakers, and researchers.

First, offshore wind (fixed-bottom and floating) plays a significant role in the North Sea energy system, comprising up to a maximum of 51

% of total power generation and 498 GW of deployments in 2050 (222 GW of fixed-bottom and 276 GW of floating wind); see Fig. 4. The technology also reduces the cumulative system cost of electricity and hydrogen system by 4.21 %; indicating wider system-level cost benefits through accelerated learning of technologies and increased hydrogen production that can be utilized to decarbonize other sectors. Further, in all the scenarios considered, the fixed-bottom offshore wind deployment reached 100 % of the estimated deployment potential irrespective of technological learning and spatial planning considerations; emphasizing the importance of this technology in reaching 2050 targets. Floating wind deployments, on the other hand, were highly influenced by technological learning, where the deployments varied between 117 and 276 GW. The North Sea countries should continue to support offshore wind development and deployment, as both technologies bring wider system benefits in terms of reduced system costs.

Second, spatial planning strategies play a crucial role in fixed-bottom offshore wind deployments. Fixed-bottom offshore wind achieved 100 % of its deployment potential in both single-use and multi-use spatial planning cases, irrespective of technological learning scenarios. Hence, realizing synergies with other marine stakeholders and limiting conflicts remains critical in maximizing the deployment of fixed-bottom offshore wind and associated benefits in the North Sea region.

Third, policymakers and industry should prioritize the commercialization of floating wind technology in this decade. The contribution of floating wind to the North Sea power and hydrogen system is highly influential towards its cost-reduction trends (Figs. 4 and 11) and a significant portion of the deployments are made after 2040. Currently, there are only prototype demonstrations in the region and two small-scale commercial projects (<100 MW) being commissioned in the UK and Norway (electrification of the O&G platforms). Increased investments and deployments are needed to commercialize and accelerate the cost reduction of the technology. Delaying such investments and support would delay the technology commercialization, challenging its competitiveness in the North Sea energy system and potentially increasing the system cost necessary to achieve targets in 2050 (Fig. 12). Moreover, the availability of an integrated offshore grid plays a crucial role in maximizing the deployment of floating wind technology and its value in the North Sea system. It was observed that the maximum floating wind deployment in the North Sea energy system declined by 70 % (162 GW from 276 GW) when offshore hydrogen production was avoided, while fixed-bottom offshore wind deployment remains unchanged.

Fourth, the role of low-TRL offshore renewables, including the tidal stream, wave technology, and bioethanol remains limited in all scenarios considered, as they remain expensive compared to other mature technologies in the system. A maximum of 8 GW of wave technology deployments were made in the year 2050 in Germany, Great Britain, and the Netherlands combined. However, this is due to the case of reaching the maximum available potential of offshore wind in the closest clusters, therefore, the next competitive technology in the portfolio was forced by the model. This observation indicates that policymakers can prioritize stimulating other low-TRL technologies if future spatial policies become more restrictive for fixed-bottom offshore wind deployments, provided the cost of resolving the arising conflicts is higher than the generation cost gap between these technologies. Moreover, the role of bioethanol from seaweed was also limited and the technology only entered the supply mix in its high-learning case, where it became competitive with the market price of bioethanol. In literature, tidal stream and wave technology were often shown as a technology that would compensate for the generational profile of wind energy and would limit the system cost increases. However, this assessment concludes that these low-TRL offshore renewables would play a limited role in the future North Sea energy system compared to offshore wind.

Lastly, the improved framework of integrating the energy system model, technological learning scenarios, and spatial inputs resulted in a better understanding of the optimal role the offshore renewables, compared to existing literature that doesn't consider these significant factors. Moreover, the estimation of spatial potential based on water depth of the North Sea (Section 2.1) allowed to better understand the role of fixed-bottom (well-established) and floating wind (emerging technology) separately, as available literature doesn't distinguish this clearly. The detailed approach in integration of significant parameters to the IESA-NS model avoided the overestimation of deployments of offshore renewables and benefits to the system. Future studies should extend this framework by incorporating the spatial constraints of onshore and cost reduction scenarios of onshore renewables as well. Although the onshore renewables are well-established and their costs are declining at an indicative pace barring external market changes, the declining public acceptance of the deployment of onshore renewables or energy infrastructure would limit their expansion and would force policymakers and investors to further explore the availability in the North Sea, an already constrained and busy area. Hence, it is crucial to consider these above-mentioned aspects in the future energy system studies and policy making.

CRediT authorship contribution statement

Srinivasan Santhakumar: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hans Meerman:** Writing – review & editing, Supervision, Project administration, Conceptualization. **André Faaij:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Rafael Martinez Gordon:** Writing – review & editing, Visualization, Software, Methodology. **Laura Florentina Gusatu:** Writing – review & editing, Visualization, Software, Methodology.

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

Data is available as a supplementary file with this article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enconman.2024.118775.

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