

Research paper

A framework to identify offshore spatial trade-offs in different space allocation options for Offshore Wind Farms, as part of the North Sea Offshore Grid

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ABSTRACT

An efficient, well-balanced North Sea Offshore Grid (NSOG) requires an area-based approach for large-scale OWF deployment. However, the essential coordination of environmental, spatial and energy planning at a basin scale is lacking. This study offers a systematic approach for unidirectional coupling of spatially explicit offshore development scenarios potentials (km^2), with an integrated energy system model, IESA-NS. Under the NSOG concept, we calculate spatial potentials for 8 predefined energy hubs (clusters). By combining the potential spatial availability, deployment and energy system costs (IESA-NS) and the risk management options (OWFs/fisheries/marine protected areas-MPA), we unfold trade-offs emerging in the planning of the future NSOG. Hence, a lower-cost NSOG, in reaching the North Sea 2050 energy targets, depends on integrated, collaborative space management, fast deployment of fixed-bottom OWFs by 2030 (3.5 times the current capacity) and multi-use with static gear fisheries (Cluster 3) and MPAs (Cluster 7). Alternatively, a higher-cost NSOG with lower impacts on the MPAs and fisheries, is highly dependent on floating OWFs (32.6GWs by 2030), from 2 British NSOG clusters. In both cases, floating OWFs are essential, the effective use of cluster space requires basin-scale collaboration (Cluster 7-Dogger Bank), and the untapped potential of Cluster 8 (floating OWFs) can lower the pressure on other NSOG clusters.

1. Introduction

The significant potential of the North Sea basin as an energy hub is fostered by the surrounding countries, bound to collaborate in hybrid cross-border projects and increased levels of interconnection, towards an integrated offshore renewable energy system (Commission of the European Community, 2021; EU Commission, 2021). The latest basin-scale political commitment, signed by Belgium, Denmark, France, Germany, Ireland, Norway, The Netherlands and The United Kingdom, aims to jointly reach 300 GWs from offshore wind farm (OWF) deployment, by 2050 (Ministry of Energy of the Kingdom of Belgium, Minister for Climate, Energy and Utilities of the Kingdom of Denmark, Minister of Energy Transition of the French Republic, Vice Cancellor and Federal Minister for Economic Affairs and Climate Action, 2023). Currently, the majority of OWF developments have been concentrated in

the near-shore areas of the North Sea basin (under 80 km from shore, with a radial connection to the onshore grid), cumulating 27.45GWs in 2020 and predicted to reach 55.6 GWs in 2025, a maximum of 110.6 GWs in 2030 and 75.9 GWs in 2050, based on ENSPRESO scenarios (Ruiz et al., 2019; European Commission, 2019).

However, these scenarios do not specifically consider the risk of spatial conflicts with alternative marine activities and protected areas and their expected additional future spatial claims. The result is an overestimation of space availability, notably close to the shore, a limited engagement with increasing offshore conflicts with other uses (Gusatu and Zuidema, 2022; Gusatu et al., 2020; Christensen et al., 2001; Jongbloed et al., 2014a) as well as long-term cumulative environmental impacts (Andersen et al., 2013; Guşatu et al., 2021; Bailey et al., 2014), associated with the planned upscaling of offshore renewable infrastructure deployment (Martínez-Gordón et al., 2022a). Furthermore,

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even with an overestimation of the near-shore availability of space for OWFs, the predicted capacity will not reach the installed 300 GWs capacity required for carbon neutrality in 2050. This highlights the urgency to consider areas of deployment further offshore. The North Sea Offshore Grid concept (NSOG) (Koivisto et al., 2020; Martínez-Gordón et al., 2022b) is among the strategic spatial allocation management options for the full marine basin. NSOG is an integrated energy system configuration that couples the energy grid of large OWF infrastructure into energy hubs, connected by HVDC cables to the shore, which is the most promoted alternative to the current radial connection (Klip, 2015).

NSOG explicitly looks beyond the current near shore developments calling for coordination and integration of strategic spatial planning for optimizing the use of offshore space and energy system planning (Gusatu et al., 2020). The current fragmented national planning limits such cross-basin coordination between multiple offshore sectors and the integration of multiple sitting criteria in energy planning are currently limited (Gusatu and Zuidema, 2022; Ho et al., 2018), essential for the spatial configuration of an economically optimized future NSOG. The major gaps in the planning of a large scale OWF deployment in the North Sea basin are the integration of spatial considerations of offshore future developments (Gusatu et al., 2020), the management alternatives for the risk of interaction with other activities and uses (Gusatu and Zuidema, 2022) and the impact on the marine ecosystem (Guşatu et al., 2021).

Energy system models (ESMs) have provided a better understanding on how to reach efficient and economically-viable solutions and pathways for a decarbonized and decentralized energy system, based on renewable resources. Although valuable, these models may underestimate the complexities of real world interdependencies, opportunities and constraints, or other physical and techno-economic factors (e.g. proximity to demand areas, distance to ports, water depth, distance to the energy grid) (Deveci et al., 2020). Moreover, accessing highly valuable sites for OWF deployment is conditioned also by the level of conflict and potential for conflict resolution with the other offshore users claiming the same areas (Gusatu et al., 2020). Hence, these energy models can benefit from a customized local-based analysis for a more detailed estimation of renewable energy potentials (Ramirez Camargo and Stoeglehner, 2018), and a clearer understanding of the spatial variability of different parameters (Martínez-Gordón et al., 2021a). While energy system optimization models for onshore areas already increasingly incorporate spatial elements in their model architecture (Sahoo et al., 2023), allowing for a more realistic representation of area-specific conditions, this has not been the case for most of the offshore energy systems. Only a limited number of energy models that include the offshore energy deployments (Martínez-Gordón et al., 2022c) also integrate to some degree the spatial elements, such as clusters based on locations of existing OWFs (Martínez-gordón et al., 2022) (e.g. IESA-NS model). In response, the central objective of this paper is to articulate a detailed approach to combine energy system modelling with spatial analysis so as to provide a practice tooling to support strategic marine spatial planning and related energy planning.

To pursue our main objective, use is made of the IESA-NS energy system model, developed for the North Sea basin (Martínez-Gordón et al., 2022d). IESA-NS follows the NSOG concept and formulates a cost optimization function which returns a single solution for each set of input parameters (e.g. cost assumptions) (Neumann and Brown, 2021). Particularly valuable for the basin scale, the IESA-NS integrated model accounts for various alternatives towards reaching the GHG mitigation targets, such as large-scale deployment of renewables, electrification of energy sectors, use of biomass, sector coupling or interconnection capacity (Martínez-Gordón et al., 2022d). In following the NSOG concept, the model optimally allocates the future OWF deployments (GWs) in a minimum number of offshore energy hubs. However, it currently does not consider actual existing or future spatial claims, which thus provides a key gap to be addressed in this study. Through this study we also compare potential socio-economic and environmental benefits and implications of each optimal allocation alternative, under different space

management assumptions.

In response, three main steps are taken to combine the IESA-NS energy system model with spatial availability. The first step is to develop seven distinct scenarios (2 primary and 5 secondary-sensitivities) that allow us to identify and calculate space availability offshore for OWFs (expressed in km^2 and GWs), capturing existing and future spatial claims from other marine uses and functions. The scenario assumptions are based on previous studies (Gusatu et al., 2020) and are highlighting uncertainties and risks in offshore interactions, as well as the continuously changing offshore developments and potential future trends (shipping, fisheries, oil and gas, military, nature protected areas) (Jongbloed et al., 2014b). Furthermore, the scenarios consider space management alternatives for the degree to which OWFs may be combined with or replace 2 other marine uses in different areas, namely fisheries and nature protected areas, for 2030, 2040 and 2050.

In the second step, the maximum potential for OWF deployment per hub, resulted from scenario spatial calculations, will represent inputs in the IESA-NS model. The IESA-NS model will optimally allocate the future OWF deployments (GWs) per energy hub, from a cost optimization perspective. The final step is to then compare the scenario performance in terms of implications of space management options, the GWs potentially available in the areas identified by the IESA-NS model and associated energy system costs. As the scenarios differ in their assumptions on spatial constraints and multi-use of space, this comparison also helps to articulate key trade-offs between alternative spatial configurations of the NSOG, under sectoral and integrated approaches, and the related energy system economic consequences.

Hence, in this paper we argue that coupling the outcomes of spatially explicit scenarios, using the NSOG spatial configuration, with an integrated energy system model (IESA-NS), is a crucial tool for a reliable and highly effective long-term strategic vision for the planning of the ambitious OWF deployment targets (300GWs by 2050) further from the shore. We also present alternatives for how to tailor the IESA-NS optimized spatial distribution of OWF deployment within the NSOG energy hub, to better integrate the current and future area-based spatial and environmental conditions and constraints. Consequently, effective and credible policy instruments (Rentier et al., 2023), setting the scene for the future NSOG in the North Sea basin, will be able to identify and promote integrated solutions that account, from an area-based perspective, for both risks and benefits of alternative solutions for OWF allocation, as part of the energy planning process.

2. Methods

In order to reach the proposed goals of this paper, we are performing a number of methodological steps (Fig. 1), further detailed in sub-sections 2.1, 2.2 and 2.3.

2.1. The energy model and the Energy deployment scenarios

In line with the NSOG concept and the energy hub interconnected spatial configuration, in this study we are focusing on areas further than 80 km from shore, hence, we do not calculate space availability for near shore developments. In the IESA-NS model calculations, the near shore area potential is covered by the scenario calculations proposed by the ENSPRESO reference scenario (Ruiz et al., 2019) (European Commission, 2019)(Table 1, Appendix A). Our area of analysis in the North Sea basin is based on spatial coverage within 8 energy hubs, as proposed by Martínez-Gordón et al. (2022) (Martínez-Gordón et al., 2022b), beyond the 80 km from shore (Fig. 2). We excluded the EEZ of Belgium and Sweden (located under 80 km from the shore). The calculations of maximum spatial availability for OWF deployment (Section 2.2) will represent a direct input in the energy model selected for the coupling of spatial data and energy system model.

For this we have selected the IESA-NS modelling tool (Koivisto et al., 2020), a cost-optimization energy system model covering the North Sea

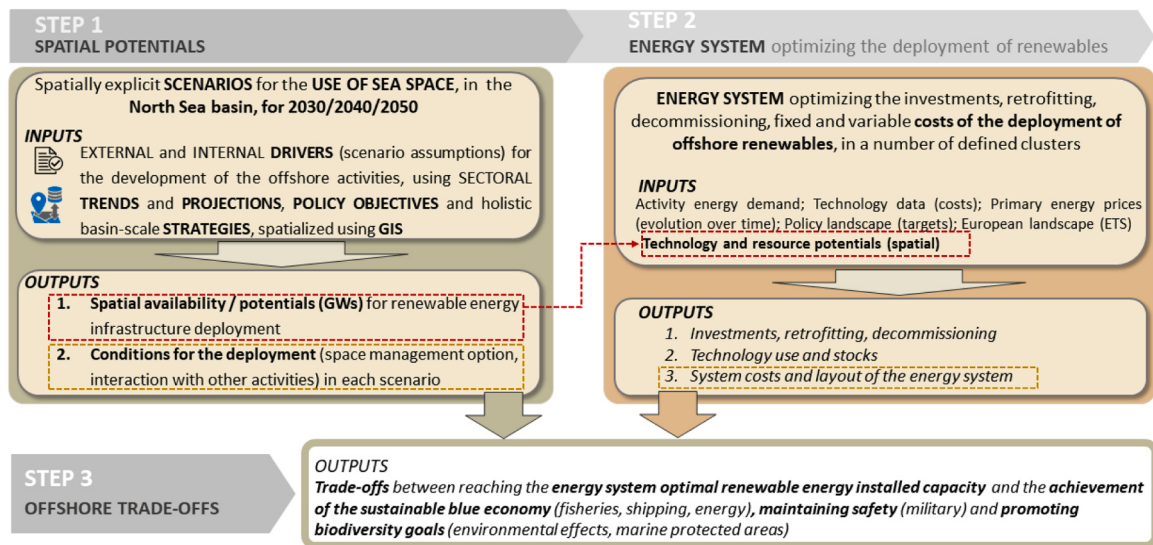


Fig. 1. Methodological steps and flow of inputs/output data between spatial analysis and energy models.

Table 1

Area of energy hubs, divided by OWF foundation type (in relation to the water depth).

Clusters	1	2	3	4	5	6	7	8
existing fixed cumulated GWs from operational, under construction, consent authorized OWFs (Fig. 2)***	4.65 (fixed bottom)	0	0	2.96 (fixed bottom)	7.7 (fixed bottom)	0	1.2 (fixed bottom)	0
fixed bottom (km^2 / % of cluster)	18445.89 (97.9%)	19777.13 (100%)	17950.6 (94.9%)	18713.17 (100%)	16282.8 (87%)	2742.58 (14.4%)	16553.94 (92.1%)	724.76 (3.7%)
floating (km^2 / % of cluster)	389.07 (2.1%)	0	955.25 (5.1%)	0	2438.76 (13%)	16289.93 (85.6%)	1420.28 (7.9%)	18627.26 (96.3%)

*** source: 4coffshore.com

region (multi-national scale) (Appendix A). The conceptual framework of IESA-NS allows for the application of an integrated spatial configuration of the offshore energy system, promoting the interconnectivity between different national energy systems, in line with the NSOG concept. Also, the model allows for an easy interaction with quantitative inputs from spatially explicit scenarios (Martínez-Gordón et al., 2022b, 2022d; Sánchez Diéguez et al., 2021; Martínez-Gordón et al., 2021b).

In following the NSOG concept, IESA-NS considers offshore energy hubs in clustered areas using centroids of operational, authorized or planned OWFs, in areas beyond 80 km from shore, hence, excluding near shore developments. Based on requirements of a HVDC interconnection (NSOG) between OWFs and energy hubs, each energy hub has a radius of 80 km (the limit up to which the HVAC cables are cost effective) (Martínez-Gordón et al., 2022c). The theoretical considerations behind the number of energy hubs and the spatial designation of the ‘best offshore hubs’ for high certainty OWF development sites are detailed in the previous study of Martínez-Gordón et al. (2022) (Martínez-Gordón et al., 2022b) and Appendix A. The result is a number of 8 energy hubs (Fig. 2) for deploying, with minimum spatial dispersion, energy-related infrastructure (OW turbines, cables, conversion stations), of which 6 hubs are based on location of existing, approved and planned OWF sites and 2 hubs are proposed based on an optimal spatial coverage (hubs 7 and 8). It is key to underline that this is a theoretical spatial configuration, based on the area-based assessment of spatial interactions, central focus of this paper.

It is only in these areas (hubs numbered 1–8 in Fig. 2) that our study subsequently analysis potential available space. The coupling between the spatially explicit scenarios and the IESA-NS model is realized through calculating the available space (km^2) in each scenario, and translating this spatial potential into OWF deployment capacity

potential (GWs), for 2 possible densities, 3.6 MWs/ km^2 and 6.4 MWs/ km^2 . The IESA-NS model requires OWF capacity potential for the 2 available technologies, fixed-bottom and floating OWF structures, dependent on water depth. This required the calculation of the potential spatial availability and capacity potential (GWs) separately for fixed-bottom OWFs (in shallow waters, over –55 m depth) and floating OWFs (in deep waters, under –55 m), using data on seabed bathymetry. Hence, the total OWF capacity in the North Sea basin for the IESA-NS model is a sum of: 1) near shore developments (fixed value across years and scenarios, Appendix A, Table 1); 2) capacity from the currently operational, under construction, consent authorized within the 8 energy hubs (fixed value across years and scenarios, Table 1); 3) potential capacities resulted from spatial scenario calculations (variable according to scenario constraints and options, Results section).

2.2. Spatial availability and scenario definition for the North Sea basin (2030, 2040, 2050)

Quantifying potential space available for OWFs in the different proposed scenarios relies on 2 variables: 1) spatial claims of existing/planned competing marine uses; 2) the degree in which these competing uses are incompatible with OWF deployment or may allow for a degree of multi-use. Both variables are expressed in the scenario narrative for 2030, 2040 and 2050, which are constructed by expanding and updating 2 scenarios developed in Guşatu et al. (2020), namely: Scenario A – integrated planning with optimistic OWF deployment trajectory, and Scenario C- sectoral marine spatial planning with pessimistic OWF deployment trajectory. Underlying these scenarios is the contrast between a sectoral and integrated planning approach (Fig. 3). In the face of increasing spatial claims for offshore activities, the planning approach

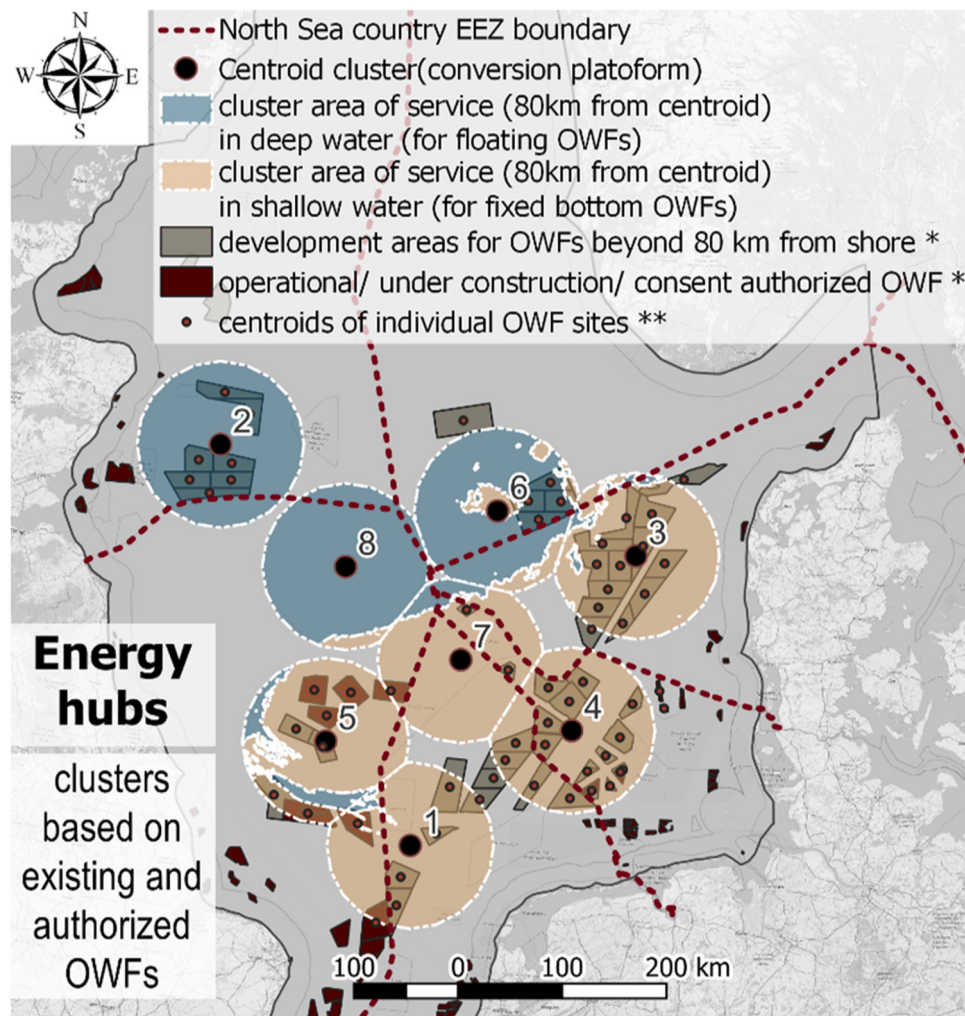


Fig. 2. Energy hubs divided by water depth (in relation to OWF foundation technology). * ‘high certainty’ OWFs (operational, under construction, consent authorized, development areas), beyond 80 km from shore. Methodology detailed in (Martínez-Gordón et al., 2022c). ** the centroids were calculated (GIS) after the initial OWF shapefiles were harmonized and divided to obtain areas of approx. 600 km².

(sectoral or integrated) is directly shaping the spatial implications of sectoral objectives and challenges (e.g., marine environment, food supply, marine transport and accessibility, defense and security, renewable energy deployment) in the marine spatial planning process (Fig. 3).

The two underlying narratives for our scenarios are operationalized in 2 base-scenarios and 5 more detailed secondary scenarios (Appendix B, Table 3). In both primary-scenarios (A0 and C0) there is no scope for multi-use, implying that they differ only in the high/low spatial claims exerted by competing marine uses from 2030 to 2050. The uncertainties linked to variability in the degree of spatial expansion of existing and planned offshore activities, as well as the degree of compatibility between offshore activities and OWFS are captured by the secondary scenarios (A1, A2, A3, C1 and C2). Hence, the secondary scenarios are testing sensitivities of assumptions for the primary scenarios. Quantifying deployment potential for OWFs (GWs), towards 2050, is subsequently linked to existing and future planned/projected spatial claims of (other) marine uses that are incompatible with OWFs.

Under an integrated planning approach (A), we propose a base scenario (A0) and 3 secondary scenarios for testing the trade-offs between different space management options: A1-fisheries, A2-nature protection, A3-balanced (Table 2). We assume a slow increase in the offshore spatial claims from future marine uses (except for OWFs), starting from the existing, new and updated MSPs. In Scenario *Integrated base-*

precautionary (A0) we assume no multi-use between activities, in scenarios *Integrated fisheries* (A1), *Integrated nature* (A2) and *Integrated balanced* (A3) we assume multi-use with OWFs, due to an increased level of congruence between sectoral goals.

Multi-use is considered between OWFs and 3 different types of fisheries, namely trawling (summarizing beam trawls, bottom otter trawls, bottom seine), pelagic and static gear. For nature protected areas (MPA, Natura 2000, SAC, areas with valuable and vulnerable species as indicated in policy documents) the multi-use is considered between OWFs and four respective protected features: birds' habitats, fish habitats, marine mammals, seabed habitats. We selected the multi-use with these 2 marine users based on previous studies indicating their large spatial overlap with valuable OWF areas in the North Sea basin (Gusatu et al., 2020), leading to increased urgency and potential from managing the risks and opportunities of these interactions (Schultz-Zehden et al., 2018; Kafas, 2017a, 2017b).

Through the lens of the sectoral planning strategy, we propose a base sectoral scenario (C0) and 2 secondary sectoral scenarios (C1-OWFs in fisheries grounds; C2-OWFs in nature protected areas). All sectoral scenarios are assuming a high increase of offshore spatial claims towards 2050, in the context of decreased inter-sectoral collaboration and increased concerns for environmental degradation, food supply and national security. A low preference for risk taking, lack of strategic vision, limited funding for knowledge advancement of risks offshore and

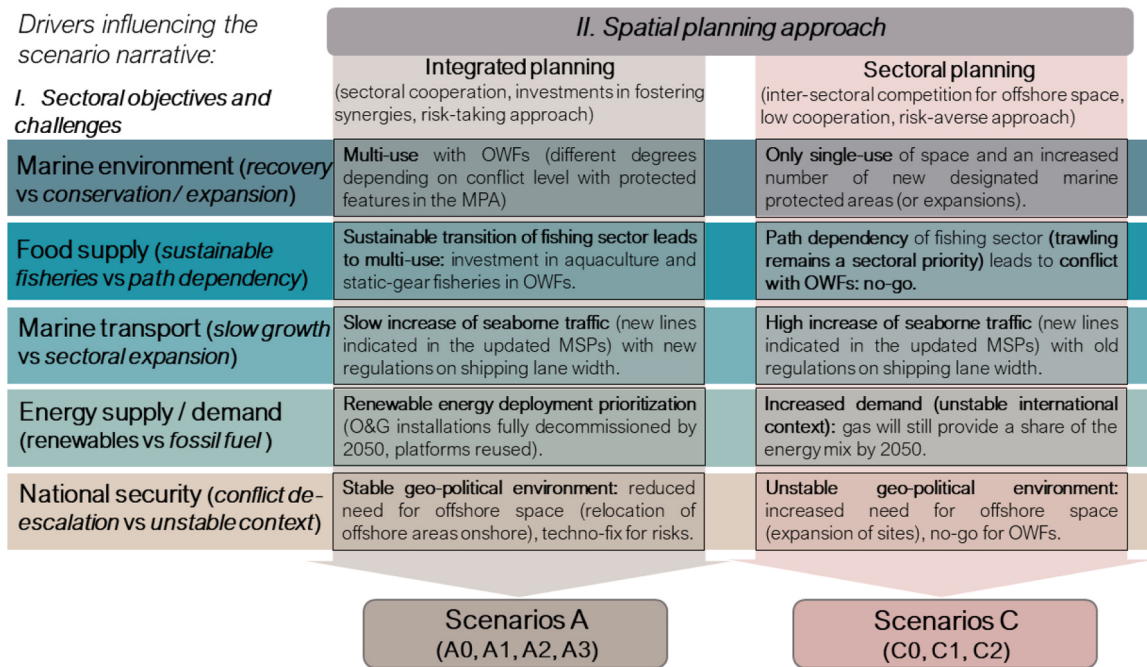


Fig. 3. Conceptual framework and spatial implications for scenarios A and C.

poor political guidance towards congruence of goals would lead to high uncertainties and a focus on the risk-avoidance and application of the precautionary principle in the management of offshore space. In avoiding negative effects of interaction and cumulative environmental pressures from OWFs, all sectoral scenarios assume *no overlap* between marine users and OWFs. However, in scenarios C1-fisheries and C2-nature, we do investigate potential to unlock additional space for OWFs, but this is not through multi-use but in effect a displacement of these uses at the cost of space for OWFs. Hence, we test the assumptions of a low focus on food supply from marine resources (C1-fisheries) and a low focus on nature protection and conservation (C2-nature) (Table 2).

The scenario visualization allows to indicate a step-wise process for locking or unlocking sites for OWF deployment, depending on the scenario assumptions. As an example, low conflict sites such as static gear fisheries in A1 and A3, or seabed habitats in A2 and A3, will have a higher likelihood to be unlocked earlier (2030) and to a higher degree (25% and 5% respectively) compared to medium or high conflict sites, such as marine mammal habitats (Appendix C). This is due to the availability of conflict resolution technologies, methods and financial support for pilot projects, required to demonstrate their effectiveness in solving, minimizing or mitigating negative effects of interaction. In assessing the likelihood of unlocking sites for multi-use with OWFs we use the methodology proposed by Gusatu and Zuidema (2022). Here, the likelihood for unlocking areas claimed by nature protected areas or fishing activities is associated with the level of conflict between OWF related activities/infrastructure and the different categories of the 2 uses (3 fishing types, 4 protected features in MPAs), directly linked to the availability of conflict resolution strategies to solve, minimize or mitigate/compensate negative effects of interaction (Gusatu and Zuidema, 2022) (Appendix D). The assumption for a lower level of multi-use with nature protected areas is in line with the current practices (authorized, operational OWFs in MPAs), derived from the precautionary principle. The aggregation of conflict levels for areas with multiple protected features and the final qualification of conflict of interaction with OWFs is detailed in Appendix D. The degree of unlocking nature protected areas for OWF deployment, in 2 of the integrated scenarios A, is detailed in Appendix C.

The calculation of spatial availability for OWF deployment is realized for 3 benchmark years, 2030, 2040 and 2050, and considers: 1) the

sectoral scenarios for the use of the North Sea basin, presenting projections of marine industries or marine uses such as shipping (Nilsson et al., 2017), oil and gas (EBN, 2016), or marine environmental protection (EEA, 2015), 2) the more comprehensive, multi-sectoral scenarios for the North Sea, on the basin scale (Gusatu et al., 2020; IMARES, 2011) or country EEZ scale (including the MSP plans) (Jan Matthijsen and Ed Dammers, 2004). The management options for the sectoral scenarios (C0, C1, C2) and the base scenario A0 allow only for single-use, while the integrated scenarios (A1, A2, A3) also consider degrees of likelihood of unlocking sites, though multi-use of space with OWFs (Table 3, Appendix C).

We quantify the space availability for OWF deployment in 2030 relying first on national MSPs for The Netherlands, Germany and Denmark, by updating the geo-spatial repository for current spatial footprints for offshore activities (QGis shapefiles) compiled in Gusatu et al. (2020) (Appendix E). For Norway, Scotland and England, we consider the current MSPs or their equivalent (e.g. Norway - Marine Management Plans), as well as potential revisions of the plans, based on current or short-terms national, European and international objectives (Government of The Netherlands, 2021a) (e.g., increase in the protection of the marine environment, restructuring of the fishing sector, etc.). As the current MSP plans do not cover the period from 2030 onwards, we qualify and quantify the development of spatial potentials towards 2040 through the lens of the proposed scenario assumptions (Table 2). For this we build on the offshore developments of the previous phase (2022–2030), to which we add potential future offshore developments and their expected spatial implications in 2040. For the timeline of the operational/under construction OWF areas, we use the available data on start operation and end operation from the data repository of previous studies (Gusatu et al., 2021) and public or commercial repositories (4Coffshore website). Last, the spatial potentials for the year 2050 are building on scenario assumptions from Gusatu et al. (2020), in alignment with developments proposed for 2040 (e.g. Appendix F, G).

For calculating the available space for OWFs we consider the degree in which offshore competing uses are incompatible with OWF deployment (all scenarios) or may allow for a degree of multi-use (only scenarios A). Subsequently, we first exclude (QGIs software) the shapefiles representing current OWF developments (status: “fully commissioned”, “partial generation”, “under construction”, “pre-construction”, “consent

Table 2
List of scenarios and main variables.

Planning approach and future spatial claims	Space management options	Conflict resolution approach (in relation to OWFs)
Sectoral approach / high increase in spatial claims: • new designated MPAs; • new shipping lanes; • extended military areas; • low decommissioning of O&G infrastructure.	C0: single-use no-go for OWFs in areas for current and future claims from other offshore uses	no inter-sectoral cooperation
	C1: single-use; no-go for OWFs (C0), and a 10% of fisheries areas are assigned to OWFs (displacement)	no inter-sectoral cooperation; 10% of high intensity fisheries areas are used for OWF allocation under risk management condition
	C2: single-use; no-go for OWFs (C0), and 2% of nature protected areas are assigned to OWFs (habitat loss)	no inter-sectoral cooperation; 2% of nature areas are used for OWF allocation under risk-management condition
Integrated approach / low increase in spatial claims: • few new areas designated for shipping lanes (in accordance to current MSPs); • high decommissioning of O&G infrastructure; • low conflict status for military / relocation for OWF development.	A0: single-use no-go for OWFs in areas for current and future claims from other offshore uses	no / limited degree of inter-sectoral cooperation (no multi-use)
	A1: multi-use in fishing grounds (A0 for the rest of the marine uses)	high degree of inter-sectoral cooperation, in particular with fisheries (multi-use of 10%, 25%, 50%, based on the conflict type, see Appendix C).
	A2: multi-use in nature protected areas (A0 for the rest of the marine uses)	high degree of inter-sectoral cooperation, in particular with nature protection areas (sequential increase of multi-use of 2%, 5%, 10%, based on the conflict type, see Appendix C).
	A3: multi-use in fishing grounds and nature protected areas (pair-wise co-location, no-go in areas of overlap between fisheries and nature areas)	high degree of inter-sectoral cooperation, in particular with fisheries (10%, 25%, 50% based on likelihood of solving the conflict with fisheries types) and nature protection (2%, 5% and 10% based on likelihood of solving the conflict with protected features).

authorized”), and the spatial coverage of other marine uses that are incompatible with OWFs, and their safety zones: telecommunication cables, pipelines, IMO shipping routes, aggregate extraction (sand, gravel), and their safety zones, oil and gas infrastructure (wells, pipelines, platforms), military areas. We do not consider major changes in the development of offshore cables, pipelines, aggregate extraction (sand, gravel), dumping sites. In sectoral Scenarios C we also exclude the nature protection areas and high intensity fishing grounds. We do not exclude the search areas, development areas or concept / early planning areas for OWFs from the available space.

Second, for the integrated Scenarios A1, A2 and A3 we map and calculate the level of multi-use between OWFs and the nature protected areas and the fishing grounds. The multi-use with fishing activity is considered in high intensity fishing grounds, with 3 categories of fishing, namely trawling, pelagic and static gear fisheries. Hence, the medium and low intensity fishing areas are considered available for OWFs. We

use the categories from the study of [Gusatu and Zuidema \(2022\)](#) and we aggregate the beam trawls, bottom otter trawls, bottom seine under the trawling category. The aggregation is due to the similar high impact scores in the interaction with OWFs. For the interaction with nature protected areas we take into account the different marine protected features (seabed habitats, marine mammals, fish species, marine birds), individually or in combination, on a case-by-case basis (Appendix D).

Hence, the areas corresponding to the 3 fisheries categories are mapped using geo-spatial data from an open repository (EMODnet) and classified based on the intensity of the fishing activity. This process is repeated for each of the analyzed years, 2030, 2040, 2050. Each of the resulting shapefiles of intersection between OWFs available areas and fisheries areas (3 types) is qualified with the level of conflict and assigned a percentage of multi-use, based on the likelihood of unlocking the site for OWFs (Appendix C). Similarly, the areas of intersection between different types of nature protected areas and available space for OWFs are qualified depending on the aggregated level of conflict with the protected features (Appendix D) and assigned a percentage of multi-use based on the likelihood for unlocking the sites (Appendix C). Last, we intersect the available space under the different space management options (single-use OWF, multi-use or displacement/overlap), for each scenario, with the service areas of 80 km for each of the 8 energy hubs ([Fig. 2](#)).

In order to account for the different investment costs related to the 2 different OWF technologies, namely fixed-bottom OWFs and floating OWFs, we split the areas of the 8 energy hubs into areas with shallow waters (above 55 m depth, suitable for fixed bottom OWFs) and areas with deep waters (under 55 m depth, suitable for floating OWFs). Therefore, the available areas for OWFs, under different space management options (single-use OWFs, multi-use), will be calculated separately depending on the water depth and will represent separate inputs in the IESA-NS energy model. Notably, the calculations for scenario-specific spatial potentials, which translate into OWF capacity potential, will represent data inputs in the IESA-NS model for the 3 benchmark years, 2030, 2040 and 2050. Furthermore, we provide the potential GWs based on the available areas (km^2) considering 2 densities ([Gusatu et al., 2020](#)), a low density of $3.6\text{ MWs}/km^2$ and a high density of $6.4\text{ MWs}/km^2$. This is a feasible range ([Ruijgrok et al., 2019](#)) when taking into account wake losses in OWF cluster configurations, one consequence of the diverse range of densities in the existing OWFs across the North Sea basin, but also the variety of potential future situations across the sea basin (e.g., potential for different densities depending on the multi-use with other uses, the technological development such as OW turbines with higher generation capacities, etc.).

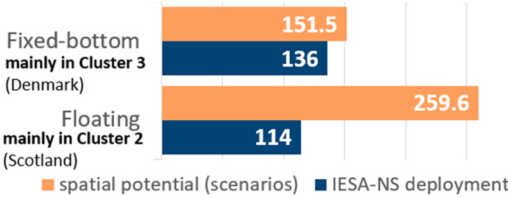
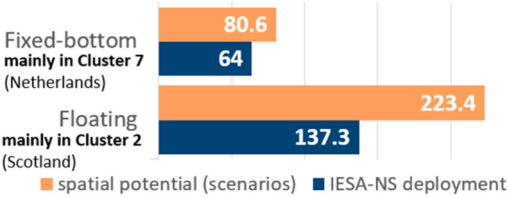
2.3. Assessing spatial implications and trade-offs between renewable energy infrastructure and other sea users

In order to emphasize the risks and benefits of each of the 5 scenarios, in the Results section we compare the outputs, namely the available space and GWs at 2 defined densities, $3.6\text{ MWs}/km^2$ and $6.4\text{ MWs}/km^2$, of each scenario, by cluster/hub. By doing this, we compare the potentials and challenges of the NSOG theoretical spatial configuration for each of the scenarios, with an emphasis on the space management type (single-use/multi-use). We then proceed by comparing the scenario outcomes in terms of OWF technology (floating/fixed-bottom), and further compare the energy system costs changes between scenarios, an output of the IESA-NS model. Last, we compare, by scenario and for each energy hub, the available risks mitigation and conflict resolution strategies required for unlocking space under different space management options, or the implications of degrees of displacement of other activities. This is realized for the interaction between OWFs and fisheries or nature protection areas

The outcomes of Step 3 will emphasize the offshore trade-offs, ranging from a minimal interaction with other offshore activities, due

Table 3

Key messages.

Scenario outcomes comparison, (2050)	A3 (most performant scenario), 6.4MWs/km ²		C0 (least ecological implications), 6.4MWs/km ²	
	Spatial scenarios potential: 411.1 GWs		Spatial scenarios potential: 304 GWs	
	IESA-NS optimal deployment: 250 GWs		IESA-NS optimal deployment: 201.4 GWs	
OWF potential and deployment (GWs in 2050)				
	Main environmental and social impacts		Main environmental and social impacts	
OWF technology and effects on system costs	Nature: highest in Cluster 5-England (7.3 GWs in 1140 km ²). - next high impact potential in clusters 7 and 8 (max 2.6–3 GWs). Fisheries: highest in Cluster 3-Denmark (static gear/trawling fisheries), followed by clusters 1 and 4.		35362.95 km ² of no-go areas for OWFs in MPAs (18.5 GWs less, compared to A3), imply lower impacts on of the North Sea marine ecosystem 31275.5 km ² of high intensity fisheries grounds with less impacts due to no-go areas for OWFs (58.72 GWs less, compared to A3)	
	IESA-NS optimized the deployment to 250 GWs (from max 411.1GWs) in 2050 Timeline: full deployment in shallow areas (76.5–136 GWs in southern North Sea) and a significant upscale in floating, from 2040, mainly in Cluster 2, from 10.4 GWs to 95.6 GWs. No deployment in Cluster 6 (Norway). lowest total energy system annualized costs. The highest reliance: fixed-bottom OWFs (54.4%, 136GWs), in clusters 3 and 7.		IESA-NS optimized the deployment to 201.4 GWs (from max 304 GWs) in 2050. Timeline: full deployment in the shallow waters by 2030, additional 32.6 GWs floating OWFs by 2040 and additional 104.7 GWs floating OWFs by 2050. 1.5 GWs floating OWFs in Cluster 6 (Norway). highest total energy system annualized corrected costs The highest reliance: floating OWFs (68%, 137.3 GWs) in clusters 2, 6 and 8.	
Main trade-offs	In the next 7 years (2030), the installed capacity should increase 3.5 times (92.5GWs, of which 13.4 GW floating OWFs). A3 scenario can reach the high ambitious energy targets by 2050 , under the minimum conditions of: full utilization of all cluster potential in shallow waters in all clusters and fast deployment of floating OWFs in Cluster 2 (75.2 GWs in 10 years). full use of shallow waters: dependent on multi-use, 36% of fixed-bottom OWF interaction with fisheries in Clusters 1,3 and 4 (47 GWs), and with MPAs, 9.7% in clusters 5 and 7 (13.2 GWs). cooperation: in Cluster 7, the cooperation between Netherlands, England, Germany is key.		In the coming 7 years (2030), the installed capacity should increase 2.4 times (64.1 GWs, of which 32.6 GWs floating OWFs). under assumptions of higher spatial claims from other activities (including in near-shore areas, not covered here), C0 has reduced potential in meeting the energy targets set for the North Sea basin. high reliance on the deployment of floating OWFs in Cluster 2 (87.5GWs) and Cluster 8 (42.2 GWs).	
	capitalizing the unused potential in Cluster 8 (72.7 GWs from floating OWFs) could lower environmental pressures , under higher costs from deploying floating OWF technology, but lower costs for mitigating risk of the offshore interactions in the shallow water clusters.		low deployments of fixed-bottom OWFs (64 GWs), where an efficient Cluster 7 is dependent on transboundary collaboration . The shallow areas of Clusters 1, 3, 4, 5 and 7 are fragmented, leading to dispersed, disconnected and, hence, inefficient hubs . a lower impact on the marine environment (no multi-use) and fisheries activities (due to no-go for OWFs) is counter-balanced by high electricity costs . Cumulative environmental impacts still remain unclear.	

to a sectoral, precautionary-based spatial planning (Scenario C) to a larger degree of interaction, under the conditions of an integrated planning approach, focused on space optimization and shared risks and opportunities (Scenario A).

3. Results

3.1. Performance of the proposed scenarios

Fueled by their different assumptions about existing and future spatial claims, the scenarios produce clearly different outcomes in terms of maximum space availability and GWs (Appendix G, H). A key difference is between Scenarios A and C, due to a lower degree of new areas designated over the analyzed timeline and the application of the multi-use concept in Scenarios A, as compared to the sectoral scenarios C. To obtain the total capacity for each scenario for the offshore area covered by the NSOG (the 8 energy hubs) we added the current fixed cumulated 16.5 GWs (see Table 2) to the calculated potential of deployment in each scenario (summarized in Appendix G, H, I). Also, in all scenarios there is a slight decrease in the space availability from 2040 to 2050, due to the new shipping lanes linking major North Sea ports and the new North Pole shipping route (a direct cause of climate change), as acknowledged

in the Dutch MSP. The final results, calculated at 2 densities (3.6 MWs/km²; 6.4 MWs/km²), are illustrated and discussed below (Fig. 5).

The most performant Scenario A3 (Fig. 6a.) allows for a maximum of 238.5–411 GWs (low/high capacity density) in 2050, with a moderate reliance on floating OWFs (66% of total OWF potential), in particular in single-use areas (80% of total floating OWF potential) (Fig. 6b.). The clusters with the highest potential for single-use floating OWFs in Scenario A3 are Cluster 2 (49.3–87.8GWs) and Cluster 8 (43–76.8GWs), in the Scottish and English EEZs, while the highest potential for single-use fixed bottom OWFs is in Cluster 7 (14.2–25.4GWs) and Cluster 4 (12–21.6GWs) (Fig. 6b).

Additionally, the higher potential for fixed-bottom OWFs, mostly in Clusters 3 and 7, shows the relevance of managing the risks and opportunities from the interaction with nature protection areas and fisheries. As fixed-bottom structures are cheaper compared to the emerging floating technologies, this is highly relevant for a cost effective system, allowing the fixed bottom OWFs (78% of the multi-use areas) to reach 12.7 GWs in 2030–34 GWs in 2050. In comparison to A0 (no multi-use), the risk mitigation space management choices in Scenario A3 unlock between 15.8 and 28 GWs in 2050 in areas of multi-use with fisheries and MPAs, with the highest contribution GWs/marine user type

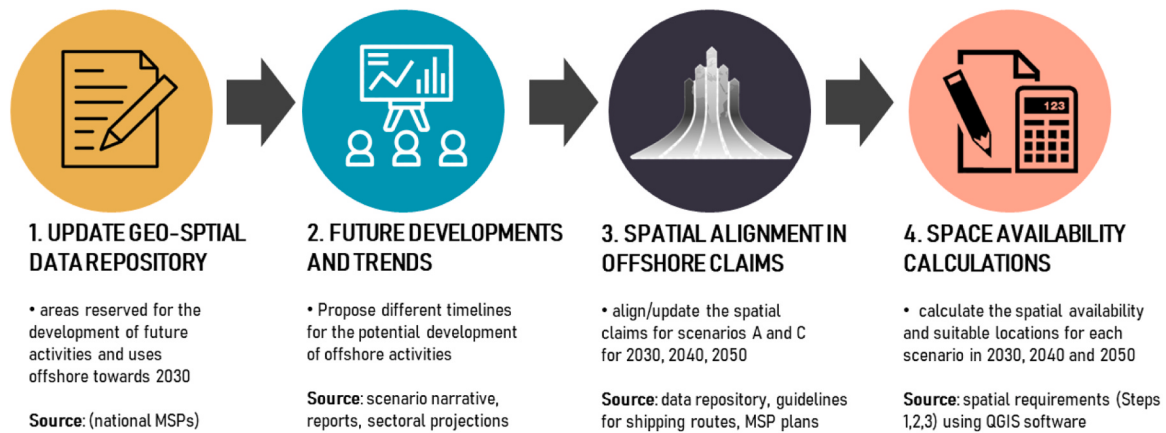


Fig. 4. Methodological steps for the quantification of spatial potentials in the proposed scenarios.

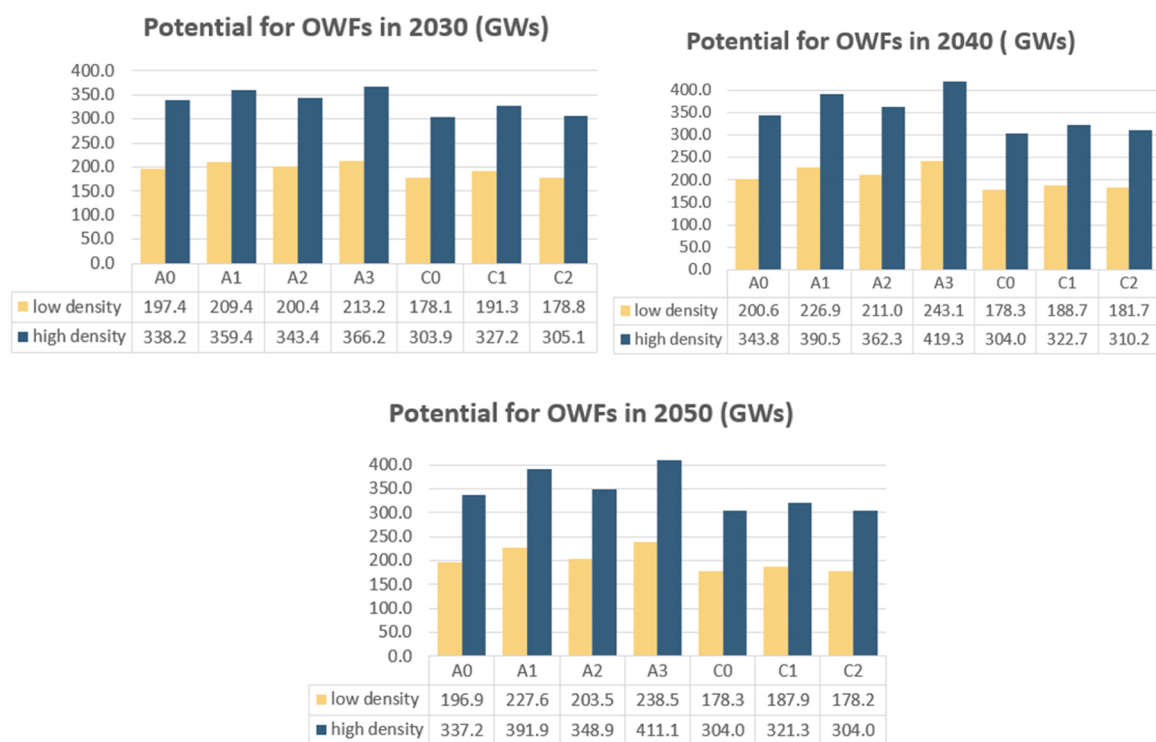


Fig. 5. Total OWF capacity potential per scenario, in the 3 analyzed years, including the existing capacity (fixed cumulated GWs from operational, under construction, consent authorized OWFs, see Table 4) and the potential capacity, calculated in all spatial scenarios.

provided from multi-use with fisheries-trawling (6.2% of total A3 potential), mainly located in Clusters 1 (3.85–6.85GWs in fixed bottom areas) and Cluster 3 (3.1–5.52 85GWs, fixed bottom areas) (Fig. 6).

The second largest contribution of GWs from multi-use in A3 is linked to static gear fisheries, predominantly concentrated in Cluster 3-Denmark, 7.42–13.18 GWs (fixed-bottom), as compared to pelagic with max.16.89 GWs gained from multi-use and dispersed across Clusters 1,2,3 and 4. This is relevant as it informs and refines the different spatial scales of approaches for unlocking space for OWFs in fishing grounds, where one option is managing the static gear fisheries in Denmark at the national scale, while another is deploying a coordinated set of measures and actions in dealing with impacts on the pelagic fisheries at the basin scale.

A lower contribution to the OWF deployment capacity of A3 is provided by the interaction with MPAs of different conservation objectives (protected features), due to a lower level of multi-use (2% - 10% of the

area of overlap. Managing the low level of conflict in the nature protected areas for seabed habitats and fish habitats would unlock 3.52–6.25 GWs in Cluster 5 and 1.41–2.6 GWs in Cluster 8 (Fig. 8). Moreover, tackling a medium conflict interaction with nature protected areas for bird habitats, and/or seabed habitats/ fish would unlock 1.3–2.3 GWs in Cluster 7.

With the maximum OWF deployment capacity (GWs) per energy hub in each scenario as input, we used the IESA-NS energy model to calculate: the total optimized electricity generation (Fig. 9a) and total annualized corrected cost of the energy system (Fig. 9b). The calculations do not include the costs of conflict resolution and risk mitigation/minimization/ compensation measures, which could unlock 60.2–107.1 GWs in 2050 for scenario A3, or the costs implied by measures to mitigate negative effects from displacing fisheries (e.g. compensation, investment in the sustainable transition of the fishing sector or financial aid for the affected coastal communities) in C1.

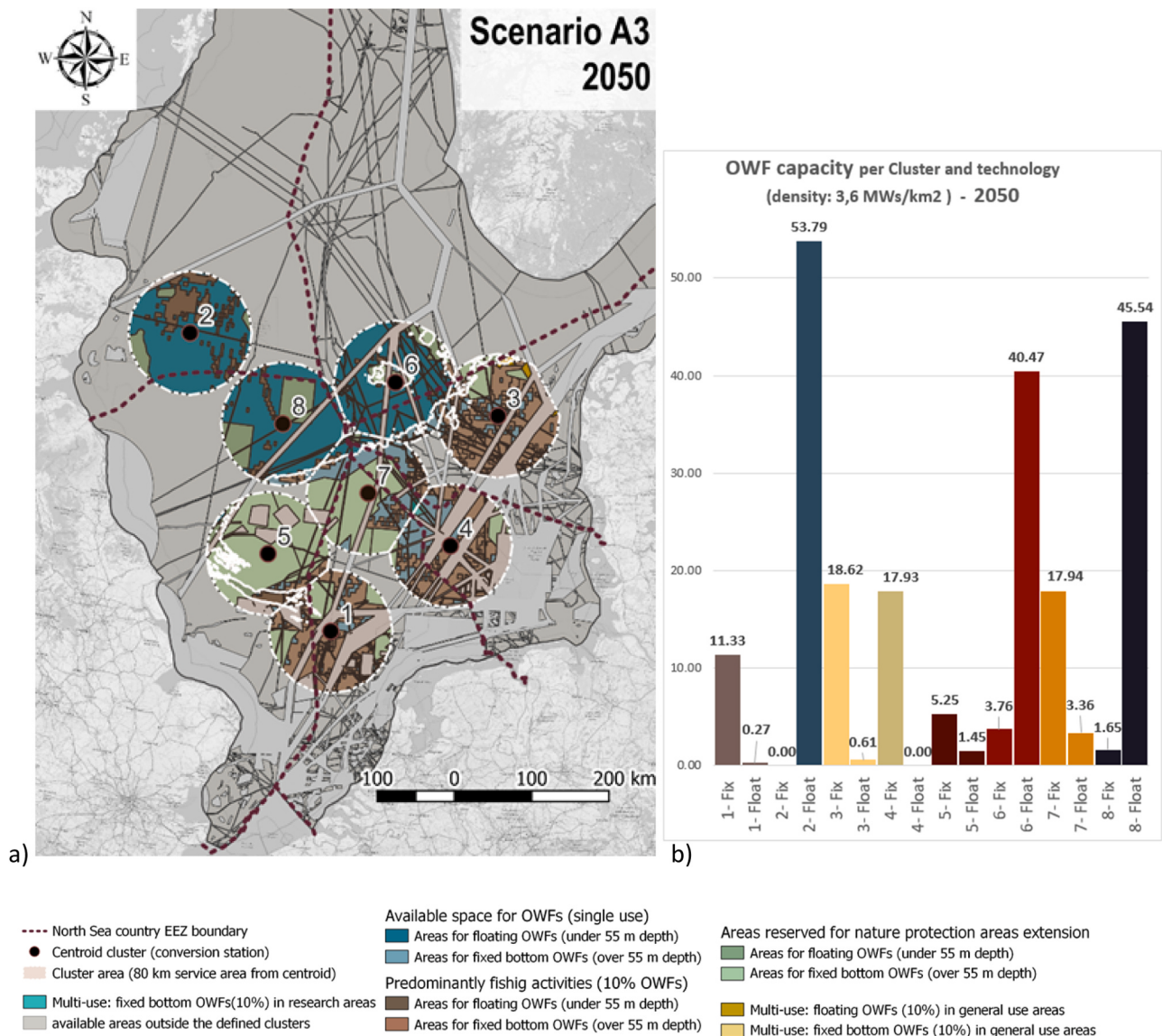


Fig. 6. a). Spatial representation of scenario A3, illustrating the different management options in relation to OWF deployment and other activities; b) OWF capacity per Cluster and technology, at a low density (3,6 MWs /km²), Scenario A3, 2050.

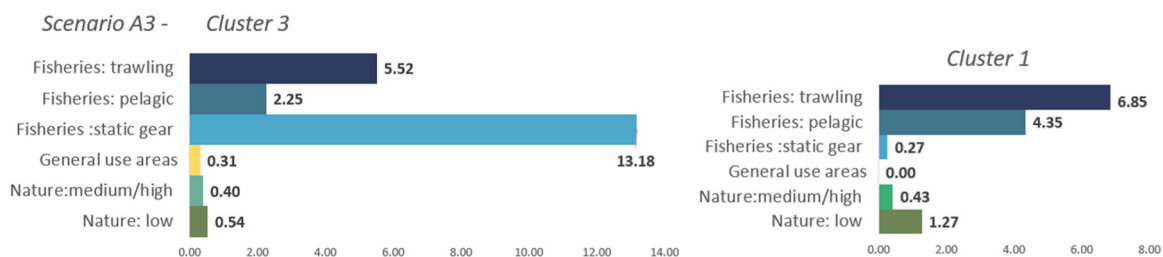


Fig. 7. Distribution of potential to unlock areas using the multi-use concept in Scenario A3, in 2050, at a high capacity density (6.4 MWs/km²), Clusters 1 and 3.

Applying the optimization of energy system cost function, with a limited deployment per cluster equal with the maximum OWF potential calculated in each spatial scenario (high density), the IESA-NS model optimized the deployment of OWFs per NSOG cluster, for 2030, 2040 and 2050 (Fig. 10). The model calculations indicate an optimal deployment of 92.5 GWs in 2030, 144.2 GWs in 2040 and 250 GWs in 2050, where the highest reliance is shifted to fixed-bottom OWFs (54.4%, 136GWs in 2050).

The IESA-NS solution implies an early and relatively balanced fixed-bottom/floating OWF deployment (54.4%/45.6%) and a full utilization of shallow waters in all clusters, as soon as 2040, with significant upscaling of floating OWFs in 2040 in Cluster 2, from 10.4 GWs to 95.6 GWs. Hence, this implies not only a high reliance on floating technology, but also a full utilization of all areas in the southern part of the North Sea basin, already under high pressure from spatial claims. Moreover, in A3, the use of 36% of the maximum cluster capacity in fixed-bottom areas is

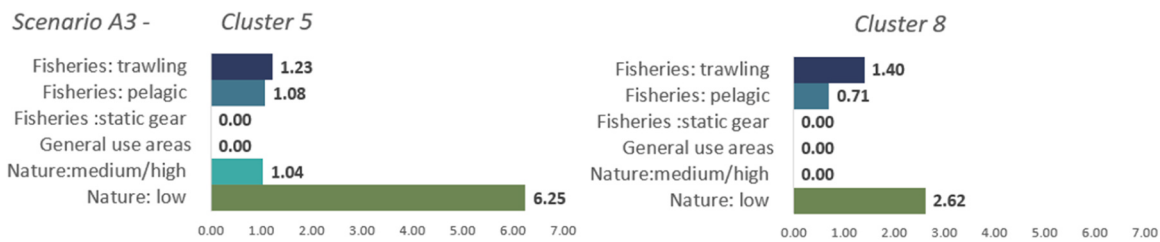


Fig. 8. Distribution of potential to unlock areas using the multi-use concept in Scenario A3, in 2050, at a high capacity density (6.4 MWs/km²), Clusters 5 and 8.

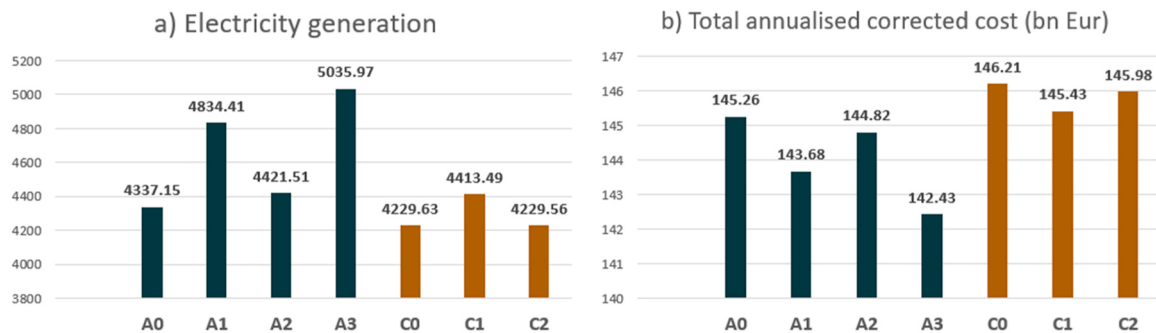


Fig. 9. IESA-NS energy system model outputs: a) electricity generation; b) total annualised corrected cost (bn Eur).

possible due to the multi-use concept with fisheries (47 GWs in 24152.7 km²). Similarly, the use of 9.7% of the cluster capacity in fixed-bottom areas is due to multi-use with nature protected areas (13.2 GWs in 27086 km²). Alternatively, lowering the pressures on the marine environment or fisheries areas would imply capitalizing the unused potential in Cluster 8 (72.7 GWs from floating OWFs). This may translate in higher costs from deploying floating OWF technology, while it may be balanced by lower costs for risk mitigation/solving of the offshore interactions in the shallow water clusters.

3.2. Scenario with the least socio-economic and ecological impact

Based on the precautionary principle, the sectoral scenario C0, the most constrained scenario for OWF deployment, assumes a low threshold for acceptable risks on the marine ecosystem in nature protected areas and the other offshore activities and increased spatial requirements of blue sectors and uses. This results in more no-go areas for OWFs for current or future activities/uses, such as extended strictly protected nature areas, shipping lanes, military areas and O&G infrastructure, up to 2050.

Hence, the OWF deployment in C0 is 178.3–304 GWs in 2050 (161.7–287.5 GWs outside existing OWF areas, Table 2) in the 8 analyzed clusters, mainly distributed between clusters 2, 8 and 6 (Fig. 11.a), with a cumulated capacity of 128.45–224.8 GWs of floating OWFs. Here, the fixed-bottom OWF capacity reaches 36–64.13 GWs, predominantly in Cluster 7 (13.5–24 GWs), shared between the EEZ of England, Netherlands, Germany and Denmark. It is, therefore, clear that the space for fixed-bottom OWFs (Cluster 7) Cluster 7 is highly fragmented, overlapping to a large extent with the Dogger Bank marine protected area, relevant not only for nature conservation but also of high interest for the location of an energy island as a result of trans-national collaborations (Energy Academy Europe and TNO, 2016; Navigant, 2017). Similarly, the available areas for fixed bottom OWF deployment (Clusters 1, 3 and 5) are highly dispersed and fragmented, allowing for only 3.28–5.83 GWs, 5.73–10.18 GWs and 1.29–2.29 GWs respectively, in addition to the existing OWFs (Table 2).

The least performing cluster in terms of available space in Scenario C0 is Cluster 5, where only 1.3–2.3 GWs can be harvested from fixed bottom OWFs (87% of available space) in 2050, due to the high conflict

with mainly nature protected areas. However, Cluster 5 also has the highest amount of commissioned, under construction or consent authorized OWFs (7.7GWs). On the other hand, the performance of Cluster 2, 6 and 8 is fully relying on the deployment of floating OWFs, while here there are currently no commissioned, under construction or consent authorized OWFs. To lower the reliance on floating OWF through unlocking space for OWFs in areas claimed by other uses, such as fisheries and nature protection, Scenarios C1 and C2 propose a sectoral approach to interaction between offshore uses. Under Scenario C1, Cluster 1 can benefit from additional 2.23–3.97 GWs, Cluster 3 can benefit from 2.53–4.51 GWs and Cluster 4 can benefit from 1.3–2.3 GWs for fixed bottom OWFs in areas claimed by fisheries (Fig. 12.a). Under the assumptions of Scenario C2, the Clusters most benefiting from the overlap with nature protected areas are Clusters 2 and 5 (Fig. 12.b).

Therefore, while posing less pressure on the marine environment and fisheries, the sectoral scenarios offer a lower performance, with OWF deployment mainly in floating areas (clusters 2,6,8) of the English, Scottish and Norwegian EEZ (C0). This is true even when unlocking space through displacing fisheries (C1, 75% floating OWFs) or when assuming a low level of impact on MPAs (C2, 74.8% floating OWFs). On the other hand, an integrated approach (A) could offer a higher performance, and diversify options for locating fixed-bottom OWFs even in the highly spatially claimed clusters in the south of the area (1,3,4,5,7).

Under the strict conditions of maximum deployment capacity calculated through Scenario C0 (304 GWs), the IESA-NS optimized the deployment in C0 to 201.4 GWs, in the 8 energy hubs, in 2050 (Fig. 13). While C0 has the lowest environmental and societal impacts among the studied scenarios, along with C2, it is the scenario with lowest total generated electricity and highest energy system costs. This can be explained by the high reliance on the floating OWF technology (68%) and low deployments in highly spatially fragmented shallow areas (64 GWs). Hence, a lower impact on the marine environment and fisheries activities (due to no-go for OWFs) is counter-balanced by high electricity costs.

3.3. Implications of scenarios on the fishing activity and MPAs in the North Sea

From both a sectoral and integrated perspective, managing the

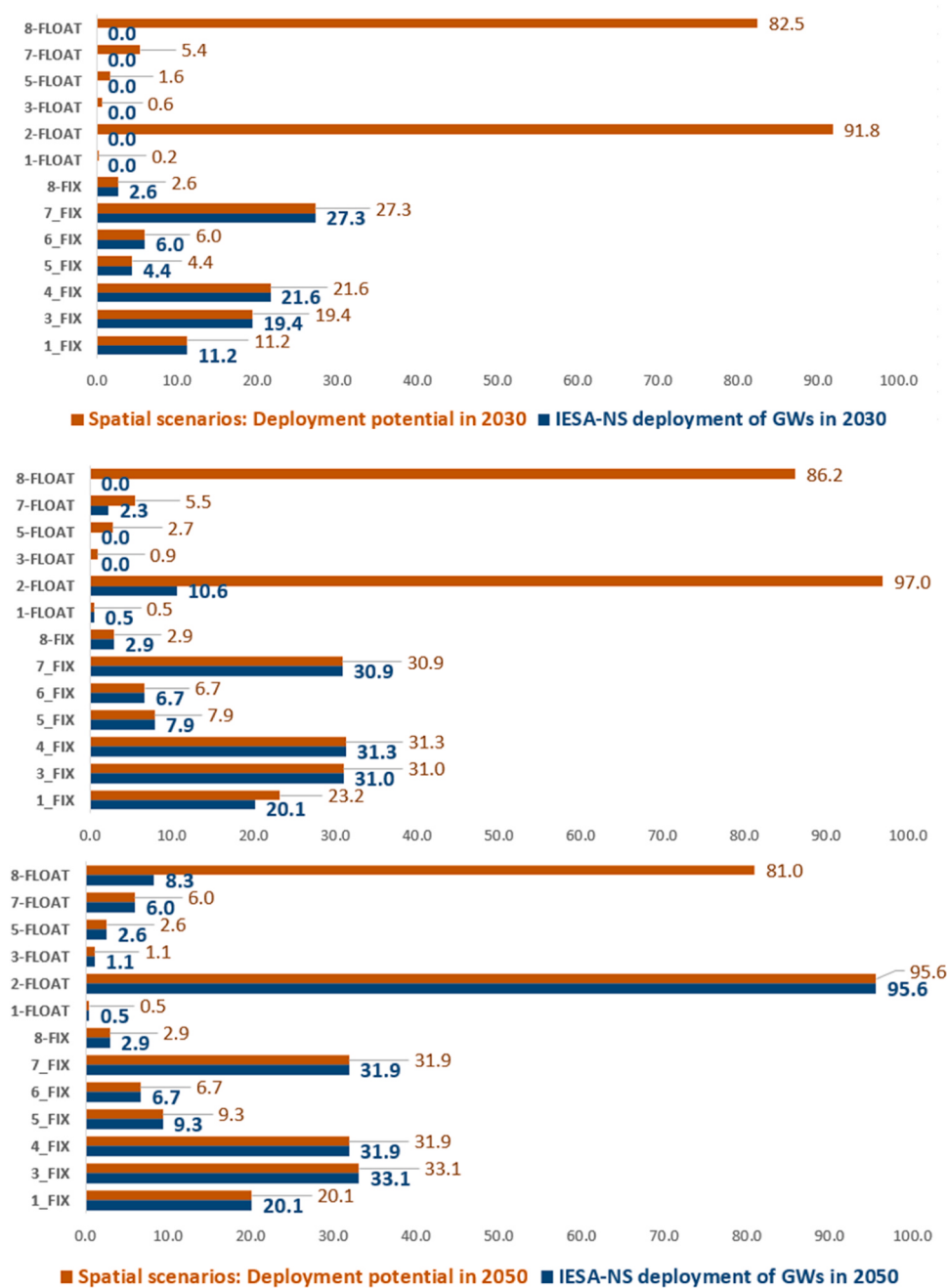


Fig. 10. Optimization of OWF deployment per cluster as resulted from IESA-NS model outputs and the maximum potential for OWF deployment in Scenario A3, under a high capacity density (6.4 MWs /km²).

interaction with fisheries provides a higher share of GWs than addressing the interaction with nature protected areas, under the assumptions of the current scenarios. Hence, Scenario C1 (OWFs displacing fisheries) provided approx. 10 GWs more than Scenario C2 (OWF in nature areas), while Scenario A1 (OWFs and fisheries synergy) provides approx. 24GWs more than Scenario A2 (OWFs and nature synergy). However, there are key differences in the socio-economic management strategies between the interaction with fisheries or MPAs, also depending on the different types of fishing gears or conservation objectives (ecosystem protected features). Furthermore, the different distributions of those uses will imply that different strategies will unlock different areas in the NSOG clusters.

Under a sectoral approach, unlocking 10% of the areas of overlap with high intensity fisheries activities, under the assumptions of a sec-

toral approach, (no multi-use) in Scenario C1, would imply the displacement of approx. 2689.5 km² of highly valuable areas for fishing activities, mainly in Cluster 3 (Danish EEZ), Cluster 1 (English and Dutch EEZ) and 2 (Scottish EEZ). To mitigate the negative effects on the fishing sector, this comes at the cost of financial compensation for the reduced revenues of the displaced fishing groups (Stelzenmüller et al., 2020) from funds such as the Dutch Transition Fund (Government of The Netherlands, 2021a), supporting the transition towards a sustainable sector (new equipment, gears, professional reconversion of fisherman to participate in the renewable energy sector, increased costs of fuel) (Stelzenmüller et al., 2020) and in support of the affected communities.

Similarly, unlocking 2% of the overlap with MPAs would directly impact approx. 187.5 km² of MPAs or designated areas for the protection of valuable or vulnerable ecosystem components in Scenario C2. To

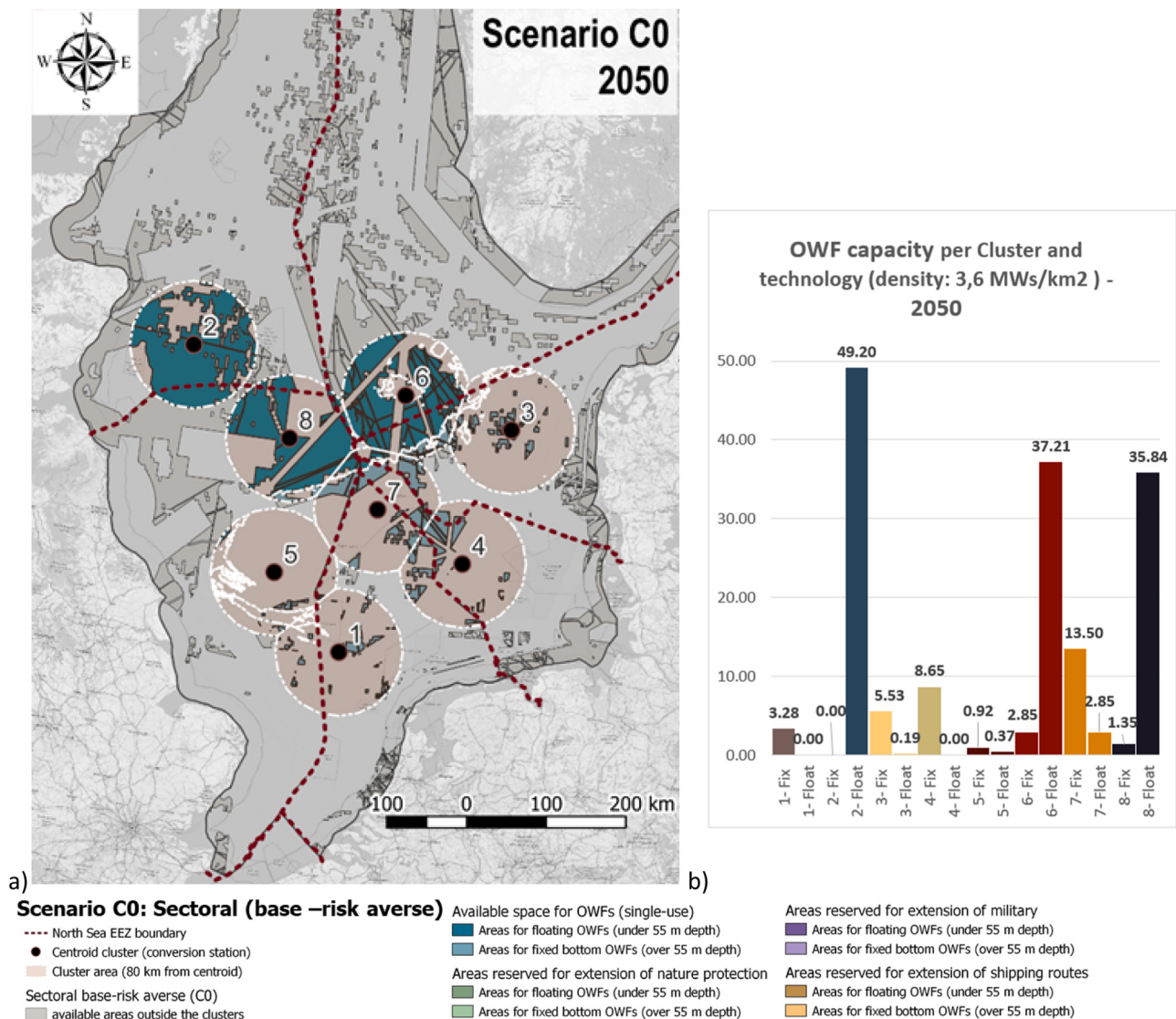


Fig. 11. a). Spatial representation of scenario C0, illustrating the single-use management option for the OWF deployment; b) OWF capacity per Cluster and technology, at a low density (3,6 MWs /km²), Scenario A3, 2050.

tackle with the potential negative effects (habitats loss, species abundance, etc.) on the ecosystem, the management measures could include the financial incentives from OWF developers to reduce the intensity of other activities offshore (such as shipping or fisheries) in sensitive areas, or implementations of measures that would improve the breeding conditions, increase the availability of prey or reduce the hunting of sensitive species (Lüdeke, 2017).

On the other side, there is a clear gain in the installed GWs in the integrated scenarios (compared to sectoral scenarios), as illustrated in Fig. 14. a, b. Here, the Scenario A1 (OWF and fisheries synergy) harvests 39.7 more GWs than Scenario C1 (OWFs and fisheries), divided between the fixed-bottom areas of Cluster 3 (10 GWs), floating areas in Cluster 8 (7.9 GWs), fixed-bottom areas in Cluster 4 (7.6 GWs). For this, deployment strategies should apply fisheries type-specific technical solutions such as layout adaptation of OWFs (bigger distanced between turbines, specific cable array design, passing through corridors) or shared insurances schemes for emergency situations (Stelzenmüller et al., 2020) in Cluster 3 (mainly static fisheries), as well as biological/ecological measures for the increase in the fish stock (Andrew Gill et al., 2020; Roach et al., 2018; Gimpel et al., 2020), compensation schemes (Stelzenmüller et al., 2020) in Cluster 4 (mainly trawling).

In terms of cost, Scenario C1 (OWF in fisheries grounds) has the

lowest cost per energy produced offshore with the highest hydrogen generation. However, the total electricity generation remains low (3rd lowest among all scenarios) while the total annualized corrected costs are high (third highest) (Fig. 9).

3.4. Contribution of areas with deep waters (floating OWFs)

Nevertheless, the largest share of GWs which can be harvested in all scenarios is located in areas suitable for floating wind farms, from a minimum of 125.6–223.4 GWs in Scenario C0 (78% of total in 2050) to maximum 145.5–258.6 GWs in Scenario A3 (66% of total in 2050). Hence, if relying only on fixed-bottom OWFs, the installed capacity in NSOG could reach only 36–64 GWs in the studied clusters in Scenario C0 (most constrained scenario), and only 76.5–136 GWs in Scenario A3 (least constrained scenario), in 2050. Furthermore, the clusters 2, 8 and 6 will be underutilized, since only 10% of their areas are suitable for fixed-bottom OWFs (Fig. 15).

Consequently, the multi-use of space can represent a viable solution for reducing the reliance on the more expensive floating OWF technology, as underlined through the results of the secondary scenarios (Fig. 14). One example is managing the interaction with fisheries (A1) which unlocks a total of 30.8–54.7 GWs, mainly in the fixed bottom

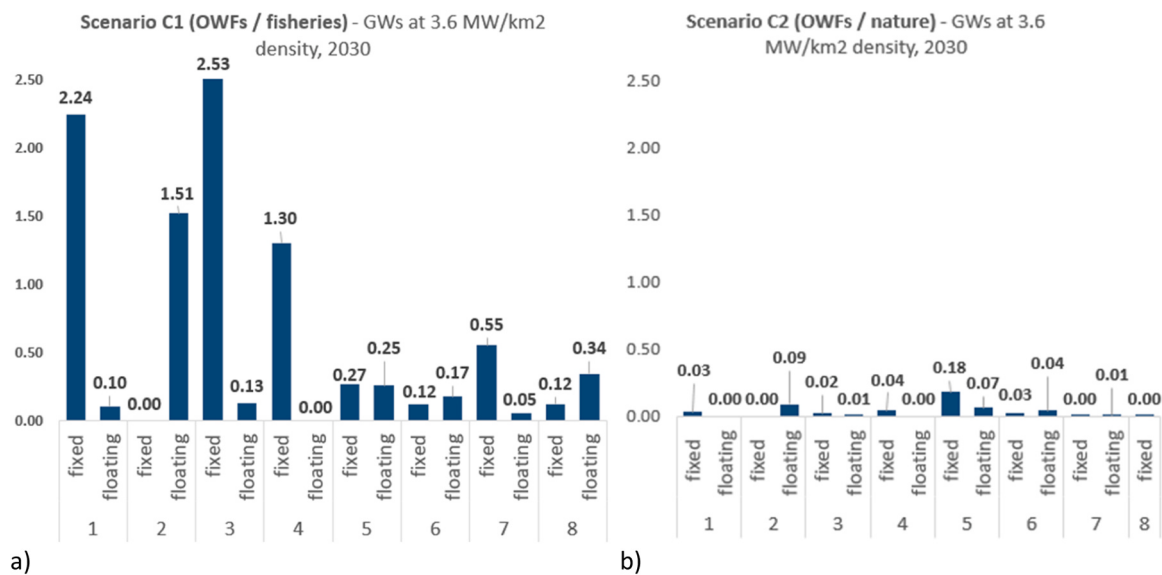


Fig. 12. Additional GWs gained (low capacity density: 3.6 MWs/km²), per cluster, in 2030 under the assumptions of: a) Scenario C1: OWFs in fisheries grounds, and b) Scenario C2: OWFs in nature protected areas.

clusters 1, 3 and 4 (clusters that add up to 23.54 GWs, low density). Due to the assumption of a low percentage of multi-use, the interaction with nature protected areas will only contribute with 6.6–11.8 GWs in 2050, in locations for fixed bottom OWFs dispersed over Clusters 1, 3, 4 and 5.

A sectoral approach to managing the offshore space (Scenarios C, Fig. 16) would imply not only a lower potential for the deployment of OWFs, with Scenario C0 allowing for 18.6–33.1 less GWs than A0, but also an increasingly higher reliance on areas suitable for floating OWFs, towards 2050 (78% in Scenario C0; 75% in Scenario A0, in 2050). The interaction with fisheries (displacement) would allow more additional areas (9.7–17.2 GWs, in 2050) than the interaction with nature areas. However, compared to the Integrated scenarios, the GWs gained in C1 are the result of displacement of fishing activities, that might be eligible for compensation of negative effects. Also, due to the precautionary approach for managing the interaction with nature protection (low % of nature protected areas allowing OWFs) and the increase in the spatial claims from other sea uses, Scenario C2 has a different trajectory of spatial availability but similar results in 2050 as C0.

The outcomes of the analyzed scenarios, both in the integrated and the sectoral approach, are indicating a high reliance on the acceleration of floating OWF technology, in particularly relevant for Clusters 2, 6 and 8, as well as a high reliance on managing the interaction with fisheries or nature protected areas, in particular relevant for Clusters 1, 4 and 3. The most relevant impact management solutions for Clusters 5 and 7 are related to habitat recovery solutions, agreed thresholds and innovations facilitating the “building with nature” concepts, specific to the distribution, status, sensitivity and conservation objectives of the identified protected features, but also a clear understanding of cumulative impacts of a large-scale OWF deployment. The energy system cost calculations for the proposed scenarios are also indicating important differences (Fig. 9) when taking into account the different spatial potentials, to which additional considerations should be given to costs of management options required by the different scenario assumptions in tackling risks of interactions with fisheries and nature protected areas.

4. Discussions

This study shows that reaching the 2050 basin-scale targets for the North Sea OWF deployment, is still uncertain under incomplete understanding of the key trade-offs made between offshore users, as well as the currently weak transboundary collaboration in developing a func-

tional NSOG. Previous studies show a range of 180 GWs (ECN - TNO, 2019), medium ambitions of 212 GWs (Freeman et al., 2019) to high ambitions of 260 GWs (North Sea Energy Cooperation, 2022) and 300 GWs (Ministry of Energy of the Kingdom of Belgium, 2023) in 2050. Under a low capacity-density of 3.6 MWs/km², and including current installed/under construction and consent authorized OWF capacity, all scenarios meet the 180 GWs target, only Scenarios A1, A2 and A3 also meet the 212 GWs target and no scenario meets the 260 or 300 GWs target. At a high capacity-density of 6.4 MWs/km², all scenarios meet the highest requirements of 300 GWs (Fig. 15). However, a uniform distribution of high density across the entire North Sea basin is highly unlikely due to the wake effect as well as potential conflicts with other marine users, as demonstrated in this study. Alternatively, space in areas outside the NSOG’s 8 clusters (configuration used in this study) allow for additional deployment, notably near shore, covered in this study and in the IESA-NS model by the ENSPRESO reference scenario calculations (European Commission, 2019). Importantly, the ENSPRESO scenario is based on the calculations of spatial availability under 80 km from shore (Dalla Longa et al., 2018), as resulted from the WindSpeed project(2009) (Veum et al., 2009), and indicates a near shore potential of 110.6 GWs, 110.6 GWs and 75.9 GWs in 2030, 2040 and 2050 respectively. However, these calculations are not fully incorporating the current situation or the future claims offshore, hence, can be considered over optimistic. While we acknowledge the potential of near-shore deployments, we focus this study beyond these areas toward a NSOG, hence, further offshore.

Faced with a potential scarcity of space, the scenario narratives of this study describe pathways for where and how space may be found for OWFs, and unfold trade-offs between different alternatives. We demonstrate that a sectoral planning approach (Scenarios C) leads to a higher reliance on floating OWFs (Clusters 2, 6 and 8), also located further away from the southern high demand areas. Alternatively, an integrated planning approach (Scenarios A) may allow for an increased use of near-shore areas for fixed-bottom OWFs, however, at a higher investment in conflict resolution strategies with nature protected areas or fisheries (Clusters 1, 3, 4, 5 and 7).

4.1. The reliance on floating OWFs

One key trade-off unfolded here is between: 1) strictly safeguarding the interests of other offshore users over the OWF deployment

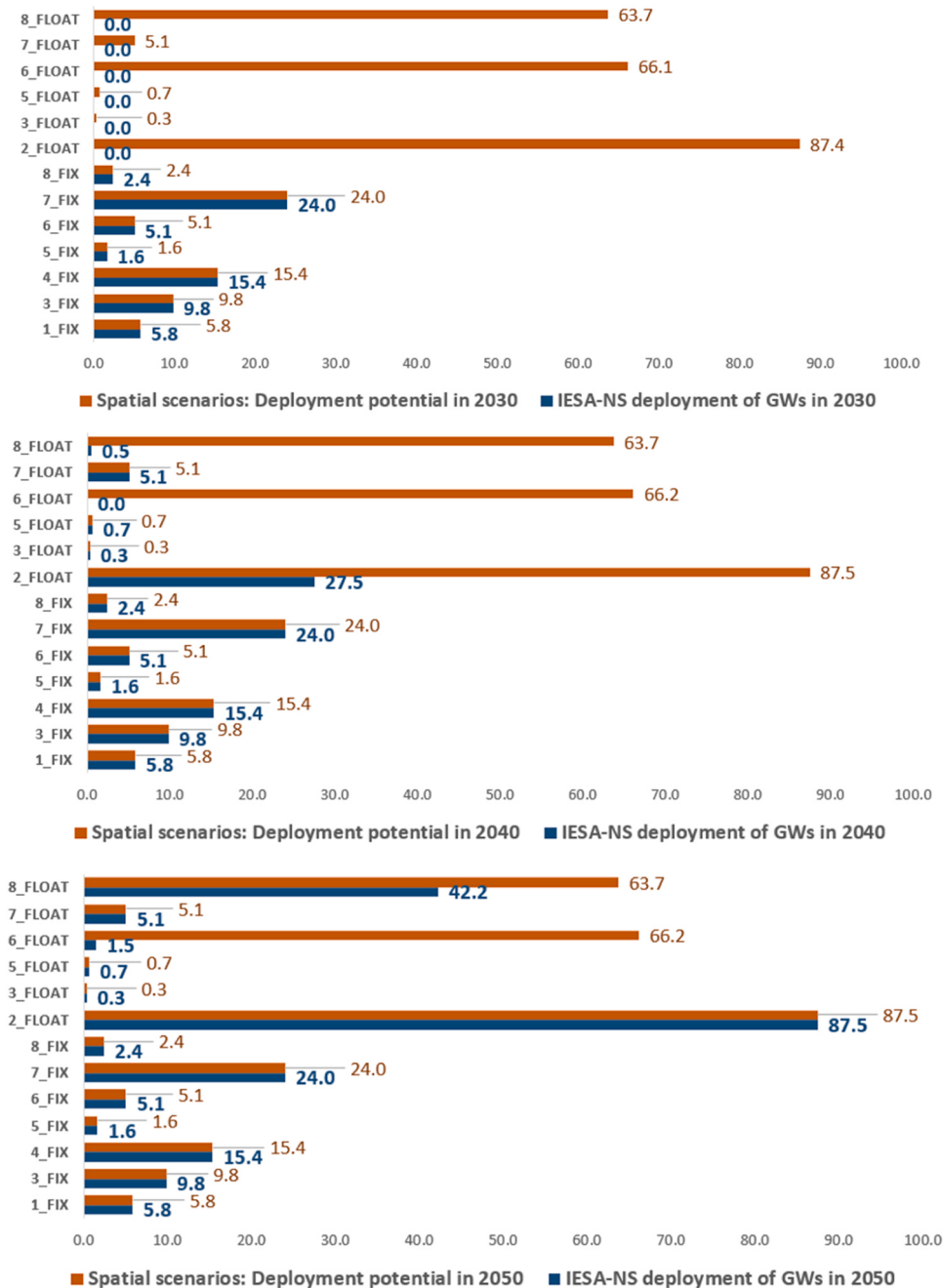


Fig. 13. Optimization of OWF deployment per cluster as resulted from IESA-NS model outputs and the maximum potential for OWF deployment in Scenario C0, under a high capacity density (6.4 MWs /km²).

(Scenarios C) which increases reliance on floating OWFs, and 2) the collaborative efforts to combine uses (Scenarios A) which unlocks areas for fixed-bottom OWFs. Consequently, Scenario C0 (sectoral) can reach low and medium OWF targets in the North Sea basin (180 GWs, respectively 212 GWs), with reduced risks of negative effects from the direct interaction between OWF infrastructure and the 2 analyzed uses. However, a proper balance of demand and supply energy flows within the different EEZs, requires a spatially balanced deployment in all the theoretical clusters, which translated into a balanced use of space and distance to the theoretical centroids in each cluster. The disadvantage of C0 consists then in the imbalance between the maximum available space for OWFs between clusters. This leads to inefficient clusters in the shallow waters (Clusters 1, 3, 4, 5 and 7, Fig. 10.a.), in particular, most notably Cluster 3 (Denmark), where there are no existing or authorized

OWFs. This undermines the primary purpose of the 8 NSOG clusters. Hence, a low potential in shallow area clusters leads to high reliance on the floating areas of clusters 2, 6 and 8, with a continuous available area due to low risk of interaction with other activities. An unbalanced NSOG also translated into higher system costs for Scenario C0, as calculated by the IESA-NS model, while also providing the lowest amount of GWs from OWFs.

Hence, a sectoral planning would imply primarily a fast deployment of floating OWFs in countries with an already high share of OWFs in the energy mix (England, Scotland) or with a low interest for a large scale deployment of OWFs (Norway, primarily relying on hydropower). This underlines the high spatial scarcity for OWF development in countries like the Netherlands, Germany and Denmark. Therefore, in particular for these countries, exploring other possibilities for the management of

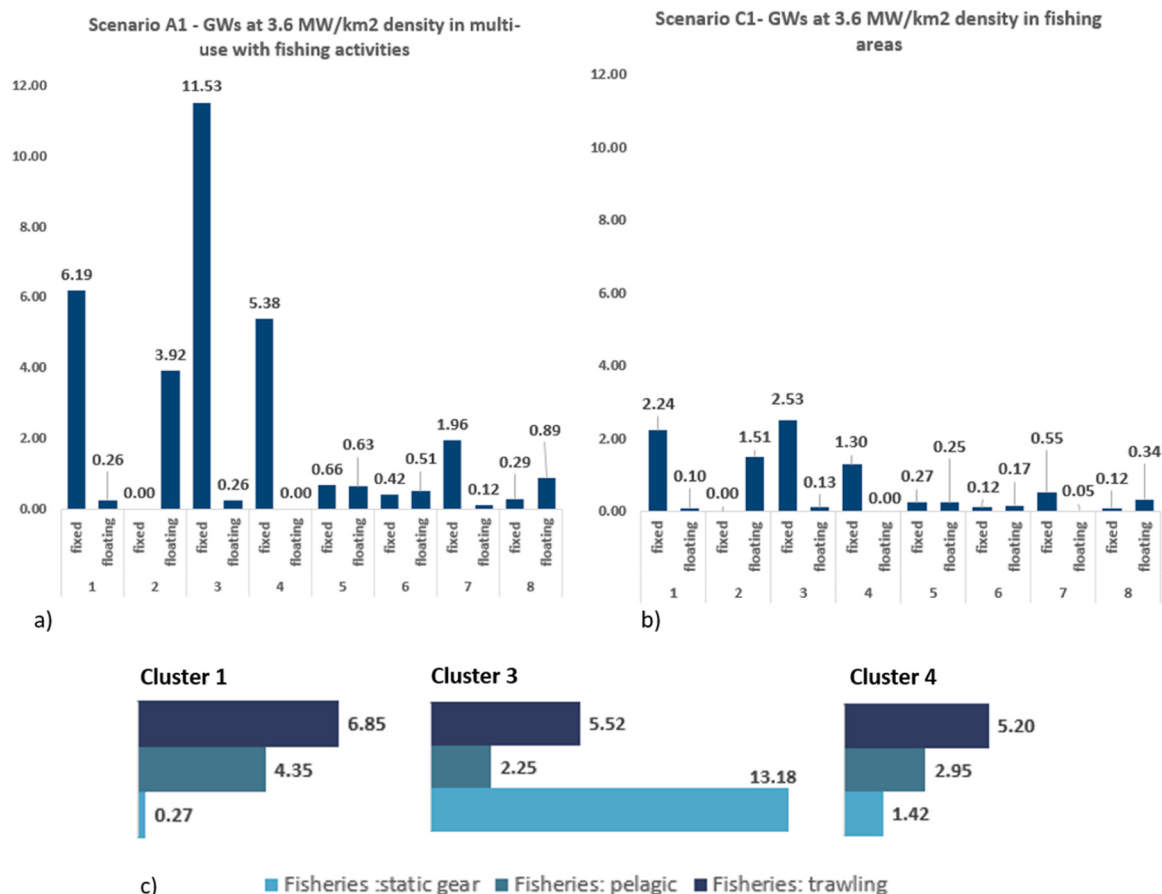


Fig. 14. a), b) Contribution to cluster deployment potential from the interaction with fisheries, in Scenarios A1 (a) and C1 (b), at a low density, in 2050; c) Contribution from different types of fisheries to the deployment potential of Clusters 1, 3 and 4, from the application of multi-use concept (high density), in Scenario A1, 2050.

a) Available space (%) per OWF technology (2030,2040, 2050)

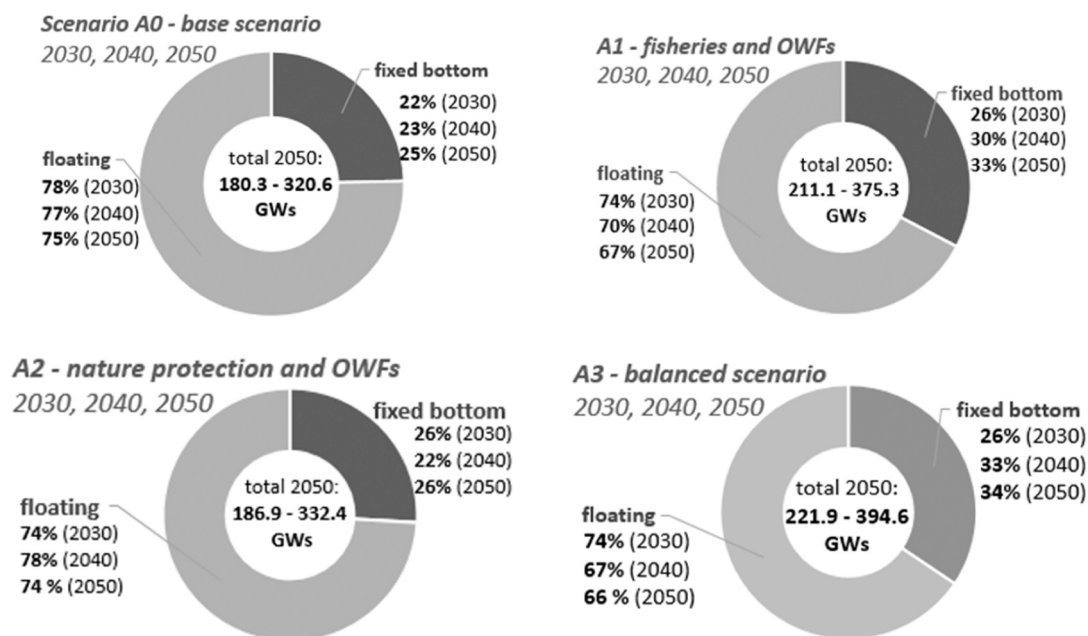


Fig. 15. a) Available space (%) per OWF technology (2030, 2040, 2050) in Scenarios A; b) Potential (GWs) in 2050, per cluster and scenario.

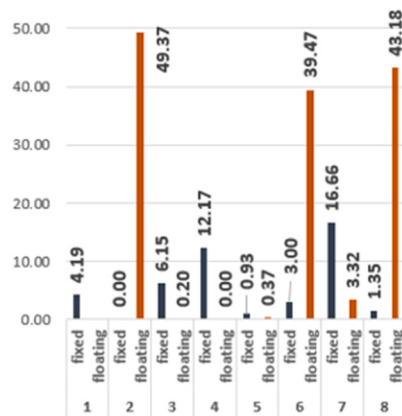
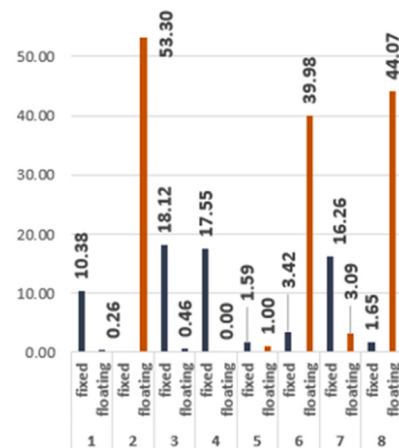
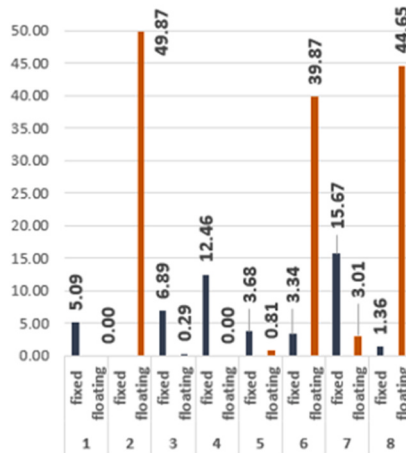
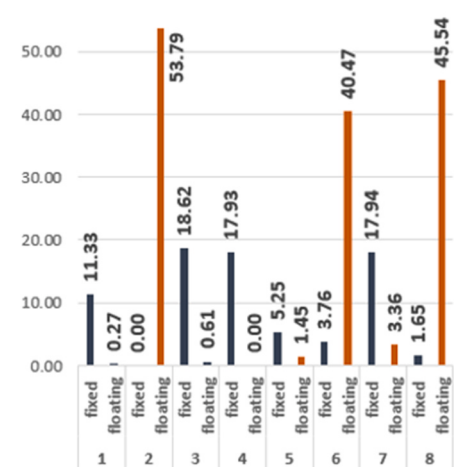
b) Potential (GWs) in 2050, per cluster, in:Scenario A0 GWs at 3.6 MW/km² densityScenario A1 GWs at 3.6 MW/km² densityScenario A2 GWs at 3.6 MW/km² densityScenario A3 GWs at 3.6 MW/km² density

Fig. 15. (continued).

offshore space (Scenario C1 and Scenarios A) becomes highly relevant.

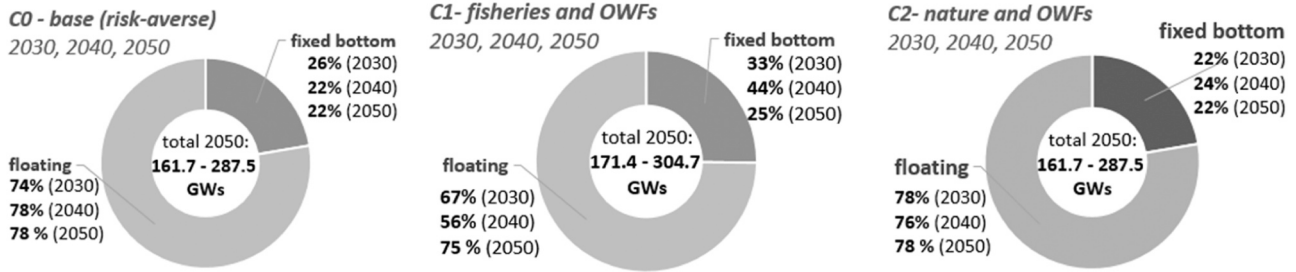
On the other hand, while Scenarios C2 and A0-A3 would decrease dependency on floating OWFs, this decrease is modest. In fact, their dependence on floating deployments in 2050 ranges from a minimum 66% in A3 (balanced scenario) to a maximum of 74% in A2 (OWFs and MPAs). The scaling up of floating OWFs from the 60.5 MWs installed capacity in 2021 in the North Sea (Yuan et al., 2023) to the minimum required of 125.6–223.4 GWs in Scenario C0 in 2050 implies consistent financial, economic and logistic efforts. The significant 65% cost reductions for floating OWFs in 2030 (down to 64€/MWh) (Fraile et al., 2021) signals a clear potential to tap into the significant spatial resources located in areas with a water depth below 55 m, essential for 66%–74% of the potential deployment capacity, in the proposed scenarios. The advantages of accessing those areas are not only reduced energy system costs but also potentially less pressure on the already impacted marine ecosystems (MPAs in Clusters 1, 3, 4, 5, 7). Importantly, it does beg for clear international flow of energy and hence collaboration across borders.

However, the optimal configuration of the proposed interconnected grid, with the 8 clusters at its core, is dependent on the deployment commitment of all the participating North Sea countries, subject to strategic political decisions. One notable example in the North Sea is Norway, with arguably low vested interests in expanding its OWF infrastructure (Moe, 2014) due to the high percentage (92%) of electricity based on hydropower resources (International Energy Agency,

2022). A lack of commitment for OWF deployment in Norway will influence the deployment potential of Cluster 6, which overlaps by 76.2% with the Norwegian EEZ and which could cause from 31 GWs (Scenario C0) to 34 GWs (Scenario A3) decrease in the total potential for 2050. This has been demonstrated in the IESA-NS optimal deployment solution in A3, where there are no investments in Cluster 6 (Fig. 10).

The 2 proposed alternatives to Scenario C0, Scenarios C1 and C2, unfold key trade-offs emerging with a lower priority of safeguarding the protection/conservation of certain MPA protected features or the displacement of low conflict fisheries. The 2 secondary scenarios allow for the comparison of potential capacity outcomes under different scenario assumptions. The trade-off in scenario C1 is made between gaining higher GWs capacity, namely 9.7–17.2 GWs in 2050 under low degree (10%) of fisheries displacement, and negative socio-economic impact on fisheries such as lower access or longer travel distances (increased fuel consumption) to fishing grounds. Subsequently, with a higher degree of displacement considered agreeable (over 10%) more areas for fixed-bottom OWFs would become available. The advantage for the NSOG spatial configuration is a higher degree of connectivity between the dispersed available areas of the underutilized Clusters 1, 3 and 5. If those trade-offs are considered feasible, there is an urgency to put in place policy mechanisms to counter-balance the negative effects on the fisheries sector, such as financial instruments for compensation. Additionally, there is a considerable decrease in the cost per energy produced offshore in Scenario C2 (9.98 Meur/PJ) compared to the base Scenario

a) Available space (%) per OWF technology (2030,2040, 2050)



b) Potential (GWs at 3,6 MWs/km2 density) in 2050, per cluster, in:

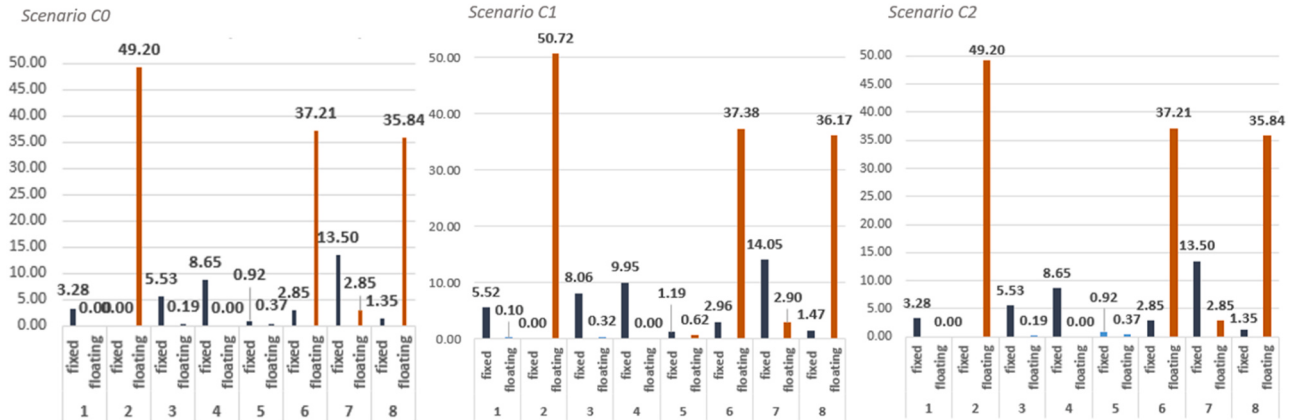


Fig. 16. a) Available space (%) per OWF technology (2030, 2040, 2050) in Scenarios C. b) Potential (GWs) in 2050, per cluster and scenario.

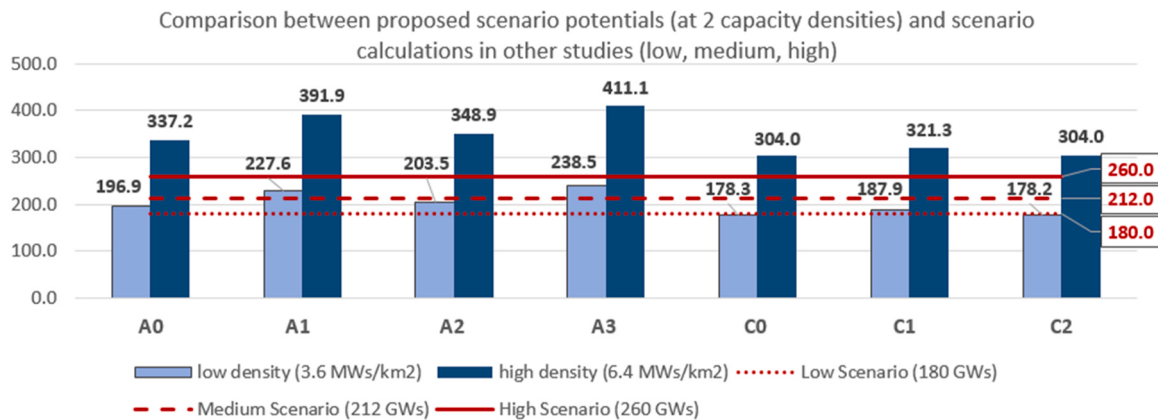


Fig. 17. Comparison between proposed scenarios (low density: 3.6 MWs/km²; high density: 6.4 MWs/km², for the area in the 8 NSOG hubs) and required capacity for 2050 targets, under scenario calculations for OWF deployment in the North Sea in other studies.

C0 (32.19 Meur/PJ), potentially due to additional 9.7–11.2 GWs in shallow waters, which may allow for heavy investments in hydrogen generation. This underlines the trade-offs between clear negative impacts on fishing activity and more total installed capacity at lower costs.

Moreover, the policy instruments and area-based strategic management planning should focus on the specific requirements of the different types of fisheries or impacted marine protected species or habitats. We illustrate this by the different spatial distribution of the fisheries types within the 8 clusters, such as the high concentration of static gear fisheries in Cluster 3, of high importance in the planning and design phases of the Danish energy island. Tackling these interactions will require targeted collaborative efforts to shared resources and knowledge through platforms and cooperation to share data, knowledge and best practices between different countries and OWF developers.

4.2. Unlocking areas through an integrated cross-sectoral approach

We demonstrate that an efficient NSOG, with a lower economic cost and environmental impact, is dependent on a cross-sectoral approach to the use of the offshore space that strategically targets policy objectives towards managing offshore risks between OWFs and other uses. The multi-use approach in Scenarios A rely on cross-sectoral collaboration for the mitigation, minimization or compensation of risks of interaction (Spijkerboer et al., 2021) between OWFs and fisheries or marine protected features in MPAs. The cross-sectoral collaboration can promote the use of technological advancements or implementation of new OWF layout design standards to accommodate fisheries or adapt to the valuable and vulnerable seabed conditions, but also foster compensation schemes supported by financial instruments such as the Transition fund (Gusatu and Zuidema, 2022). To exemplify, the cross-sectoral

collaboration between the energy sector and the maritime transport sector or fisheries is particularly relevant for Cluster 4 and 1 (IMO routes/new links to the new North Pole Route). The consideration of “passing through routes” for trawling would unlock min. 2.93 GWs and 3.85 GWs (low density) in Cluster 4 and 1, while the integration of the pelagic fisheries in the OWF layout design would unlock min. 2.45 GWs and 1.66 GWs (low density) in Cluster 1. The clusters most benefiting from a cross-sectoral approach in dealing with the interaction with fisheries are located in the most spatially scarce areas of the North Sea, namely Cluster 3 (11.8–20.96 GWs), Cluster 1 (6.45–11.46 GWs) and Cluster 4 (5.38–9.57 GWs). Similarly, unlocking space for OWFs in Clusters 5 and 7 requires primarily a proper understanding of impacts on valuable seabed habitats and/or marine mammal’s habitats. This allows for cross-sectoral efforts (policy framework, financial instruments) towards implementation of “building with nature” solutions for unlocking min. 3.52 and 1.3 GWs in the 2 clusters.

4.3. Reflection on clusters

An optimal spatial use of the 8 NSOG energy hubs, equally covering a cumulated area of 160 848 km², is key in the balanced spatial configuration of the NSOG. In this study we demonstrate that the theoretical NSOG spatial configuration cannot be considered realistic without taking into account the offshore spatial realities of the area. Furthermore, it cannot be considered optimal when approaching the spatial planning through a sectoral perspective. This is further emphasized by the conflictual spatial location of adjacent OWF infrastructure such as transportation cables or the hub conversion stations, spatially located in the cluster centroids for the Clusters 1, 3, 4, 5 and 7. This conflict is clear under sectoral scenarios C0 and C2, with the spatial overlap between the theoretical location of energy hub centroids (conversion stations) and the SN10 shipping priority areas (German EEZ), under projections of shipping intensification and stricter safety measures.

Another example of spatial conflict that implies a trade-off between OWF infrastructure and other uses is the theoretical location of the centroids (conversion stations) for Clusters 5 and 7, situated inside the Dogger Bank MPA, resulting in potential impacts on the protected seabed habitats. Technical solutions such as the German MSP designated area LN1 for bundling submarine cables (Bundesanzeiger, 2021) can help minimize impacts of cables between hub OWFs and the conversion station. These technical solutions are feasible for clusters overlapping the EEZ area of one country, however, become a matter of trans-boundary cooperation and strategic planning for clusters overlapping the EEZ of multiple countries, such in the case of Cluster 7.

Integrating marine spatial planning in energy system planning at the basin scale also allows for a reflection on national targets for OWF deployment. For example, reaching 72 GWs in 2050 (Government of The Netherlands, 2021b) in the Dutch EEZ, within the Development Areas 1, 2, 3 and 7 (overlapping Cluster 1) and 5 and 6 (overlapping Cluster 4), as part of NSOG, could be fully achieved in Scenario A3 and partly in Scenario A1. However, both scenarios do require employing management strategies tackling risks of interaction with pelagic fisheries (both clusters), trawling fisheries (both clusters), while Scenario A3 also requires employing management strategies with low/medium conflict nature protected areas (Cluster 1). Similarly, fully deploying approx. 10 GWs planned in the screening areas (energy island) within the Danish EEZ could be achieved in scenarios A1 and A3 when tackling the risks and opportunities with pelagic fisheries in Cluster 3, while not overlooking the still unknown and under-researched environmental effects of an energy island. Towards this, the results of this study can inform design decision on the construction alternatives for the Danish energy island, where the more restrictive scenarios in terms of OWF deployment (Scenarios C) would allow for a deployment of maximum 5.53 GWs (Scenario C2) to 8 GWs (Scenario C2) in 2050.

4.4. Informed choice of the approach and tool

The methodological strength of the proposed framework stands primarily in the ability to integrate a number of key aggregated results from previous studies, including an integrated energy model (IESA-NS) with 7 quantified and qualifies spatially explicit scenarios consolidated in this study. While this offers a holistic understanding of the major trade-offs, a number of limitations should be discussed. First, the outcomes of our approach can vary depending on the scenario assumptions used, one example in this study being the percentages associated to the feasible and acceptable utilization or overlap between OWFs and fisheries grounds or MPAs (Appendix C). This entails that the results presented in this paper are not to be considered final and unchangeable. Hence, the flexible framework of the proposed methodology allows for the consideration of different percentages of feasible overlap, depending on a number of factors such as the status of the MPA protected features at the species population level or in accordance to conservation objectives. Similarly, the agreed level of overlap with valuable fishing grounds can vary in space and time depending on the level of cooperation and accessibility of conflict resolution options with local fisheries communities (small scale fisheries) or industry (large scale fisheries). In addition, one key potential improvement of the current framework is the additional information on impacts of external factors on spatial scenarios, most notably from changing environmental conditions due to climate change. Valuable inputs include potential changing patterns of valuable habitats distribution, due to increased sea acidification and growing temperatures (Poloczanska et al., 2013), as well as changing patterns of human activity (such as fisheries) due to changing marine ecosystem dynamics affecting marine food webs (Doney et al., 2012). The framework can also benefit from improved data on cumulative effects of human activities and mitigation measures to address those effects. The flexibility of the proposed framework allows for the future addressing of the current limitations of this study. This underlines the versatility of the method proposed, which can reflect area-based degrees of ecological protection or possibilities for relocation of fishing activities.

Nevertheless, the coupling of a spatial model for calculating offshore potentials, in different scenarios, with an energy system optimization model, can present uncertainties related to the level of aggregation of input data. From a spatial consideration, this aspect has been tackled through proposing alternative scenarios for the management of offshore space (compared to the base scenarios A0 and C0). From an energy model consideration, those uncertainties have been extensively presented in the paper by Martínez-Gordón et al. (2022a).

Also, the scenario assumptions of Scenarios A are not considering the potential for multiple overlapping activities with OWFs, due to the precautionary principle. Due to cumulated risks emerging from the interaction of more than 2 activities, in the OWFs area, we exclude from the potential available space the areas where nature protection overlaps with fisheries, military activities, shipping, etc. This can however be considered in future studies, when accounting for the spatiality of the water column (three dimensionality of the water body) and the different activities taking place at the different levels.

Last, the study can benefit from better spatialization of scenarios, through more reliable representation of projected spatial claims of other marine activities (shipping, military, etc.). Also, future studies could also focus on a more realistic representation of the available areas near-shore, outside the NSOG clusters, which are currently covered by the calculations ENSPRESO reference scenario.

5. Conclusion and policy implications

A spatially optimal, technically feasible and cost effective North Sea wind power Offshore Grid (NSOG), with a fair distribution between countries, that also accounts for societal benefits and the North Sea ecological carrying capacity, will not be possible without incorporating

the spatial dimension and area-based constraints in the energy planning. Current practices for the energy planning offshore have a weak spatial planning component and are primarily focused on national deployments (Gusatu et al., 2020; Guşatu et al., 2021). In this study we have demonstrated that by integrating the spatial interface to an energy model we can obtain valuable insights in the alternatives for an optimal utilization of space, while not overlooking key trade-offs to be considered in the early stages of the energy planning process. This was realized from a spatial management scenario perspective, and by incorporating existing knowledge on levels of risk with different types of fisheries or MPA protected features, as well as associated risk mitigation strategies, leading to an area-based qualification and quantification of trade-offs. Nevertheless, we demonstrate that not only national-scale institutional integration and cross-sectoral harmonization (Spijkerboer et al., 2021), but crucially basin-scale strategic planning that is integrating environmental, spatial and energy planning processes, are issues that require special policy attention towards reaching the 2050 energy goals.

Furthermore, policy aimed at the setting the legal framework for the future NSOG should prioritize integrated solutions that foster potential synergies between OWFs and other marine users, while having a particular focus on potential risks of interaction. Through comparing the 7 spatially explicit scenarios, we conclude that a sectoral approach (Scenarios C) would lead to a high reliance on the deployment of floating OWFs (Clusters 2, 6 and 8) and an unbalanced NSOG, with underutilized clusters in the shallow waters (1, 3, 4, 5 and 7). On the other side, an integrated approach (Scenarios A), would allow for higher deployment of fixed-bottom OWFs, under conditions of management measures for reducing risks of interactions offshore (e.g. trawling fisheries). Such management measures can range from OWF design layouts incorporating static gear fisheries in concentrated areas (Cluster 3) to trans-boundary collaborative efforts for reducing the risks of interaction with seabed habitats, seabirds, fish and mammal's habitats (Clusters 5 and 7). The methodology and findings of this study can inform policy instruments in the initiation support mechanisms, such as the Building Obligation Scheme, or co-investment grants²⁷ in support of OWF projects that deploy certain technologies with a reduced risk of interaction with other marine users, under a clear understanding of implied trade-offs. A number of highlights of the paper are summarized in Table 3.

Most importantly, adding spatial data to energy models is essential in producing realistic, area-based outcomes, informing the timely and strategic coordination of environmental, spatial and energy planning in the design of the NSOG. Alternatively, the risk lies in guiding the space management through the current sectoral interests (Spijkerboer et al., 2020), leading to fragmented, nationally-oriented planning of future OWFs, and an expensive and underutilized NSOG. This would potentially not deliver the required installed capacity to reach the 2050 energy targets, or do that at a high socio-economic or environmental cost.

Hence, the proposed framework for coupling aggregated spatial and related risk management elements into energy models primarily addressed the methodological gap of providing realistic and area-based results. Importantly, the framework also demonstrates the potential for informing strategic energy planning process and policy formulation on a basin scale level, when considering area-based characteristics. Nevertheless, the results of the proposed framework can greatly benefit from improved knowledge on the impacts of OWF pressures on specific species, habitats or fishing types, as well as the consideration of alternative technical solutions for large projects such as the Danish energy island, energy storage or CCS projects. This is attainable due to the flexibility of the proposed framework which can incorporate new inputs, making it relevant for the strategic planning of OWF developments in various sea basins worldwide.

The results of the study underline the urgency to address the energy transition in the North Sea basin from a long-term strategic planning perspective, building on cross-border collaborative efforts for creating a common, integrated North Sea vision. The strategic planning of the NSOG should be supported by coherent, integrated and inclusive

governmental, legislative and regulatory frameworks, to better capitalize synergies and more effectively address conflicts, within the ecological boundary of the North Sea ecosystem.

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CRediT authorship contribution statement

Srinivasan Santhakumar: Software, Investigation, Data curation. **Rafael Martínez-Gordón:** Software, Investigation, Data curation. **André Faaij:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization. **Christian Zuidema:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization. **Laura Gusatu:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Laura Gusatu reports financial support was provided by European Union, under the Marie Skłodowska-Curie grant agreement No 765515, <https://cordis.europa.eu/project/id/765515>.

Data availability

Data will be made available on request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.egyr.2024.05.052.

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