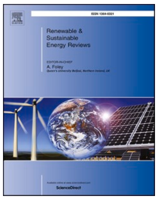
Renewable and Sustainable Energy Reviews 154 (2022) 111794

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



Global assessment of historical, current and forecast ocean energy infrastructure: Implications for marine space planning, sustainable design and end-of-engineered-life management

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ARTICLE INFO

Keywords:
Ocean energy infrastructure
Offshore renewable energy
Design
Decommissioning
Marine spatial planning
Socio-economic-environmental balance

ABSTRACT

Thousands of structures are currently installed in our oceans to help meet our global energy needs. This number is set to increase with the transition to renewable energy, due to lower energy yield per structure, growing energy demand and greater and more diverse use of ocean space (e.g. for food, industrial or scientific activity). A clear and comprehensive picture of the spatial and temporal distribution of ocean energy assets is crucial to inform marine spatial planning, sustainable design of ocean infrastructure and end-of-engineered-life management, to prevent an exponentially increasing asset base becoming an economic and environmental burden.

Here we define the spatial and temporal dimensions of the challenge that lies before us through creation of a comprehensive global dataset of past, current and forecast ocean energy infrastructure and offshore energy resources, both hydrocarbon and wind, for the period 1960–2040. The data is collected together for the first time and made available in the public domain through an interactive online map. The resulting oceanscape provides insight into the type, quantity, density and geographic centres of the accumulating asset base, which in turn enables informed consideration of how marine space alongside design and end-of-engineered-life of ocean infrastructure can be managed responsibly and sustainably.

1. Introduction

[1]Many thousands of structures are installed in oceans around the globe providing populations with energy both from fossil fuels and renewable sources, and the amount is increasing. Results from this study show that as many structures have been installed in oceans in the last decade as were installed in the 50 years before.

From the infancy of the offshore oil industry in the US in the 1950s to the end of 2020, approximately 6000 fixed or floating platforms [1] and a network of subsea infrastructure have been installed in our oceans to extract a combination of oil and natural gas. Currently, more than a quarter of global oil and gas supply is produced offshore [2]. While offshore hydrocarbon exploration has slowed, offshore oil and gas production has not – oil production has been relatively stable since 2000 while natural gas output has increased more than 50% in the same period [2] leading to continued construction of oil and gas developments in our oceans.

Offshore electricity generation from wind power has grown rapidly

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[1] Freely available online interactive map https://www.arcgis.com/apps/mapviewer/index.html?webmap=9205cfceff1744609cffbbdc315b0408 Animation demonstrating features and functionality of interactive map https://youtu.be/QbyYu5gh_3g.

https://doi.org/10.1016/j.rser.2021.111794
Received 17 November 2020; Received in revised form 18 September 2021; Accepted 15 October 2021

since 1991, when the first commercial offshore wind farm, Vindeby, offshore Denmark, was commissioned [3], to a global capacity of more than 34 GW at the close of 2020 [4] from over 5000 turbines, mainly concentrated offshore Europe [5]. While growth has been exponential, offshore wind still contributes only 0.3% of global electricity generation [6]. Predictions, however, suggest offshore wind has the potential to generate more than 420,000 TWh per year - more than 18 times global electricity demand today, noting that currently electricity constitutes less than 20% of our global energy consumption [6].

World population is forecast to increase from 7.8 bn in 2020 to 9bn by 2050 [7] while the world economy had been predicted to more than double by 2050 [8], far outstripping population growth. Increasing global population and wealth will drive an increased demand for energy, forecast at 50% between 2018 and 2050 [9]. Reconciling increased energy demand with the necessary decarbonisation of our energy system, formalised through targets of the Paris Agreement [10], will drive the continued growth of the renewable energy sectors, including offshore wind and other offshore renewables.

Renewable energy structures have a lower yield per structure than hydrocarbon structures so many more are required for the same energy output. Considering the annual yield for a large oil or gas platform [11–13] and a 'large' fixed-base 7 MW offshore wind turbine [14] indicates somewhere between 1200 and 1900 offshore wind turbines are required to produce the same amount of energy as a single offshore hydrocarbon platform. The embodied energy in a renewable energy production facility is minimal compared to a hydrocarbon facility of comparable capacity [15,16] and the need for a transition to renewable energy is not under question - but the volume of the asset base required to meet demand is significant, and necessitates more careful consideration of how marine space, design and end-of-engineered-life of ocean infrastructure should be managed.

This paper sets out the size and shape of the challenge by collecting for the first time, data on the spatial and temporal distribution of energy infrastructure in our oceans, globally over the period 1960–2040, set against a backdrop of offshore energy resources, infrastructure types and options for decommissioning at the end-of-engineered-life. Economic, environmental, social and legislative considerations relevant in shaping the future design and decommissioning agenda for ocean energy infrastructure are discussed, emphasising the need for balance between each to ensure responsible and sustainable management of our oceans in the transition to renewable energy.

2. Data, methods and created resource

Data on past, present and forecast energy infrastructure over the period 1960–2040, spread across the world's oceans and seas has been synthesised from a range of open access [17–19] and commercial [1] sources. This includes information on facility type, location, date of installation, date of decommissioning and variably further details such as number of turbines. These data have been augmented through reference to individual development project websites and documents associated with the planning process. The resultant database was analysed in relation to contextual data (e.g. bathymetry, wind characteristics and identified hydrocarbon reserves) and visualised within a geographical information system (ArcGIS Pro) and quantitatively represented through graphs. In addition, kernel density analysis was undertaken to provide easy to interpret time-slice outputs illustrating changing intensity of use of ocean space. In this paper, static maps alongside graphs developed from the data are presented to illustrate trends, drawn from the dataset created as part of this project. An interactive map, created from the database developed as part of this project, has also been made available online to allow readers to engage with their own areas of interest. The interactive map enables exploration of development of offshore energy infrastructure from 1960 to 2040, allows users to focus globally or on a specific geographical location, and sort by infrastructure type. The interactive map can be freely accessed online at: https://www.arcgis.com/apps/mapviewer/index.html?webmap=9205cfceff1744609cffbbdc315b0408.

A video abstract of the interactive map can be viewed here: https://youtu.be/QbyYu5gh_3g and video supplements are provided alongside the static maps presented in this paper (see links in captions).

3. Results

3.1. Spatial and temporal mapping of ocean energy infrastructure and resources

Fig. 1 shows the current density and distribution of offshore energy infrastructure for hydrocarbons (1 A) and wind energy (1 B) globally, against a backdrop of known offshore energy resources and ocean bathymetry (water depth). The data shows existing development is concentrated in areas of plentiful and accessible hydrocarbons, with pockets of offshore wind resources starting to be harvested, predominantly in the shallow waters of the continental shelf and close to centres of high population (to minimize tieback to shore).

Fig. 2 shows the current and forecast distribution of operational offshore energy infrastructure, i.e. start-up assets minus decommissioned assets, for both hydrocarbon and wind generation, for the present day, 2025, 2030 and 2040. The increase in number of structures between 2021 and 2040 is particularly visible in North West Europe, with the seas around China and Japan also demonstrating dramatic shifts in density. This increase is largely driven by rising numbers of offshore windfarms. Fig. 2 also demonstrates how offshore decommissioning activities will shift globally. While the Gulf of Mexico represented the area of highest density of structures between 1960 and 2000, the introduction of offshore renewables has altered this market, with the North Sea and Yellow Seas becoming critical loci.

3.2. Time series trends of ocean energy infrastructure

Fig. 3 graphically represents time series of installation and decommissioning activities for offshore hydrocarbons and wind energy in terms of (A) number of projects and (B, C) number of structures (notably renewables projects comprising many individual structures). It is clear from Fig. 3A that at the project level, activity in the oil and gas sector still outstrips that seen for offshore renewables – offshore wind projects being almost imperceptible. Considering the spatio-temporal data in the interactive map, notable forecast expansion in offshore oil and gas is seen in Africa and Malaysia.

However, in terms of sheer number of structures (Fig. 3B and C), which drives the volume of the asset base, offshore windfarms demonstrate a shift in the scale and location of our interaction with the world's oceans and seas. Contrasting Fig. 2 alongside the data shown in Fig. 3B and C, the impact of offshore wind developments on geographical density of total offshore activity becomes more apparent. Variation in total density of structures is driven by offshore windfarm activity and is concentrated offshore NW Europe and Asia. Fig. 3C further shows that by 2040 there are forecast to be twice as many offshore renewables structures in the oceans as oil and gas structures.

4. Discussion

4.1. Offshore infrastructure – type, composition and end-of-life fate

The amount and distribution of current and forecast offshore energy infrastructure is set out in Section 3 – but what does this infrastructure look like, what is it made of and what happens to it at the end of its productive life?

Offshore structures evolved for oil and gas extraction from fixed platforms in shallow waters to floating platforms in deeper waters (Fig. 4). A range of subsea architecture (i.e. sits on the seafloor and remains submerged) also exists, and can be tied back to a fixed or floating

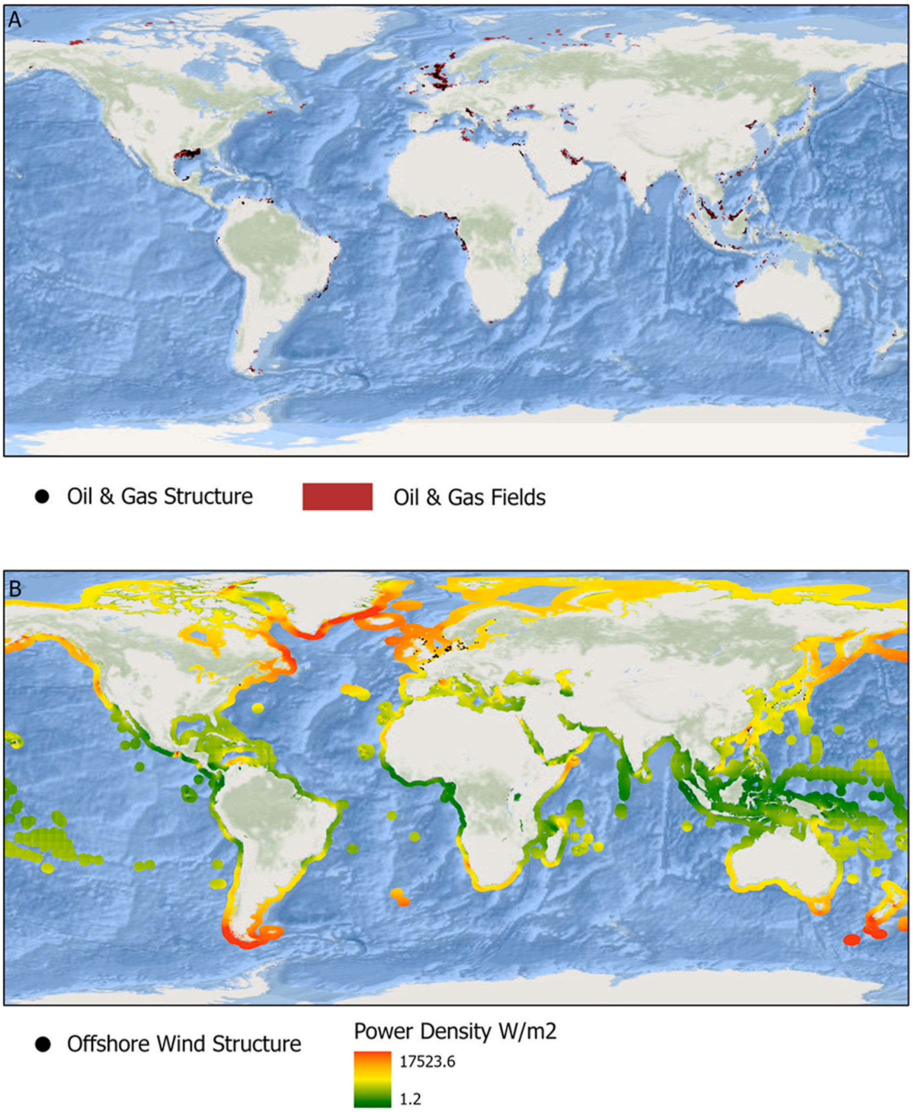


Fig. 1. Current (2021) distribution of ocean infrastructure and known offshore resources for (A) hydrocarbons and (B) wind, showing concentration of ocean development in areas of plentiful and accessible resource, close to shore to minimize transport to consumers. Data sources: Rystad [1], Emodnet [17], BOEM [18] & Geoscience Australia [1]. Cartographic data from ESRI, GEBCO &De Lorme. The spatial distribution of ocean infrastructure and resources can be explored interactively via the online map, or viewed dynamically (but not interactively) at the video links https://youtu.be/Z3s19tAKt94 for Fig. 1A, https://youtu.be/XAQtP9Wkz1E for Fig. 1B.

platform or directly back to shore. Offshore wind turbines are predominantly fixed directly to the seafloor on steel monopiles (large diameter steel tubes) that penetrate into the seabed, and above the seabed transition into the mast to which the turbine is attached, while some fixed wind turbines are supported on steel braced structures with so-called 'bucket' foundations (because they resemble an upturned bucket). Floating offshore wind concepts are more closely borrowed from the offshore oil and gas industry, adopting a traditional tension leg, spar or semi-submersible style.

Oil and gas infrastructure is predominantly constructed of steel – whether foundations, substructures or topsides (see Fig. 4) – with the exception of concrete gravity based substructures. Monopiles and masts for fixed wind turbines are also fabricated from steel, but turbine blades are composite structures, usually glass fibre and less commonly carbon fibre. Steel is widely recyclable, although no industry-wide statistics are available on percentages recycled from decommissioned offshore energy assets, and foundations are generally left in situ at the end-of-engineered-life rather than retrieved for recycling. By contrast, composites are not easily recyclable, in part due to the thermoplastic resins that bind the composite together. It is also noteworthy that the design life of offshore wind turbines is around half that of a typical hydrocarbon platform, 25 years compared to 50 years or more. These factors set a new challenge for the offshore energy sector in managing the end-of–engineered-life of wind energy developments [20].

As an example of the potential end-of-engineered-life challenge of offshore wind turbine blades, a typical 6 MW wind turbine has a blade length of 75 m (approximately the same length as an A380 aeroplane wingspan) and mass per unit rated power of 12.58 tonnes/MW [21], i.e. 75.5 tonnes per blade and 3 blades per turbine. With 16,435 wind turbines forecast to have been installed in our oceans by 2040 (Fig. 3), this sets up a significant volume of composite to manage at the end-of-engineered-life.

The current default for end-of-engineered-life of offshore infrastructure is complete removal of the structure from the ocean and recycling or disposal onshore with the intention to return the seabed to its initial state [22], and while precedence exists for alternatives e.g. 'rigs-to-reefs' [23,24], where infrastructure is repurposed in designated zones to create artificial reefs, these are not widely adopted [23,25].

With use of the ocean clearly set to increase, existing design paradigms of offshore infrastructure must be challenged to account for end-of-engineered-life, to ensure sustainability, to reduce the volume and embodied energy of infrastructure, and ensure that structures are designed for decommissioning, e.g. suited to reuse, recycling or natural degradation [26–29].

In the following sections, we explore how existing offshore infrastructure could be decommissioned, and future offshore infrastructure

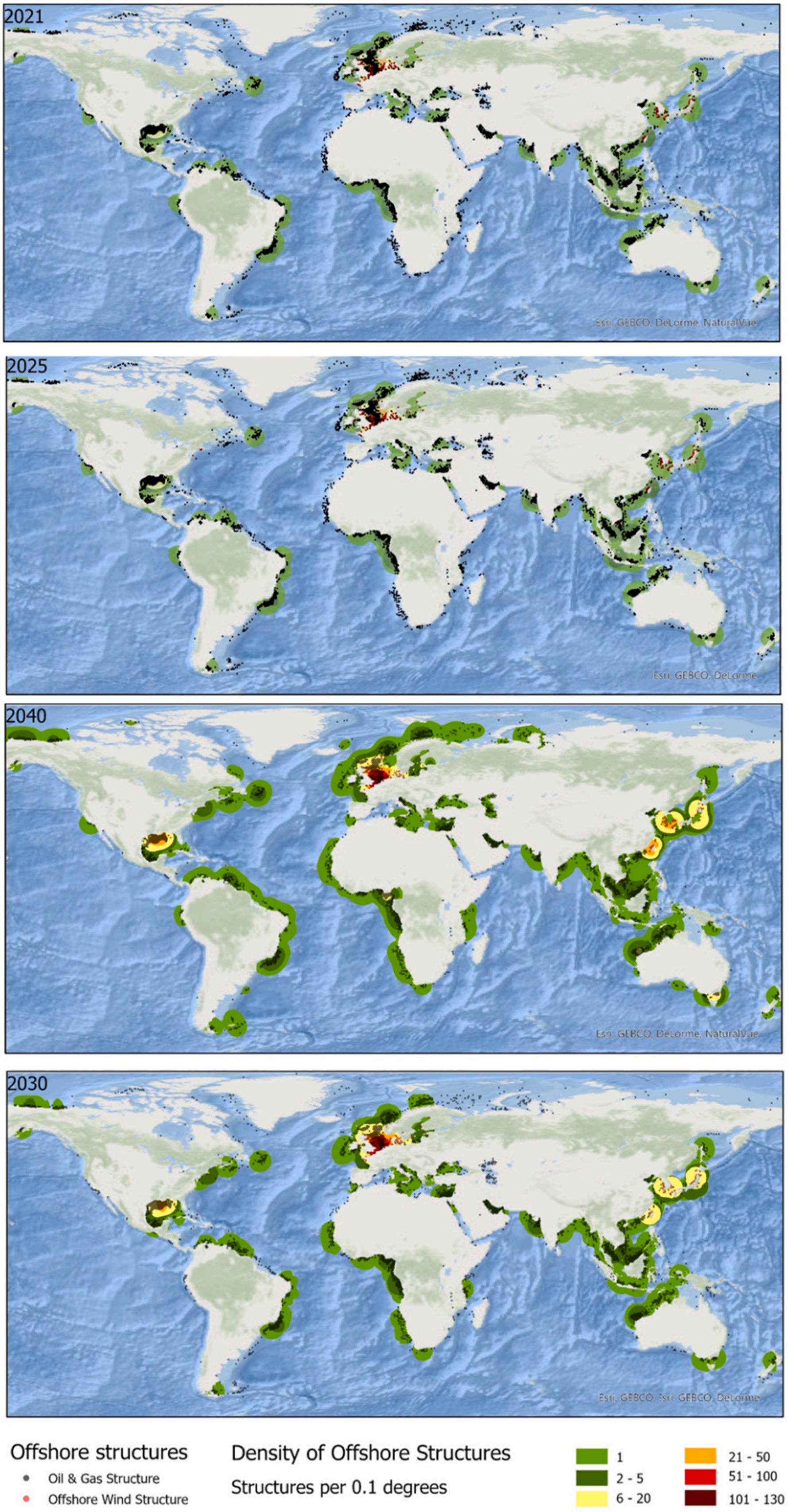
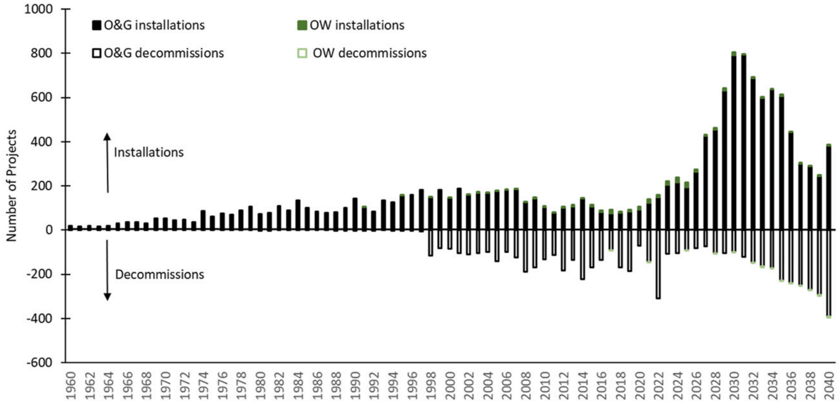
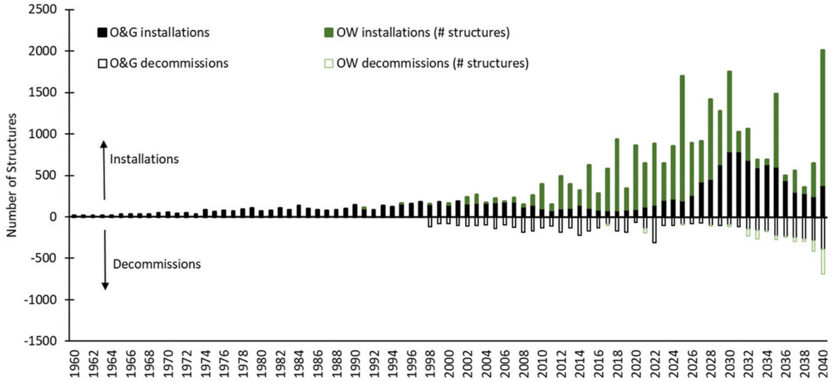


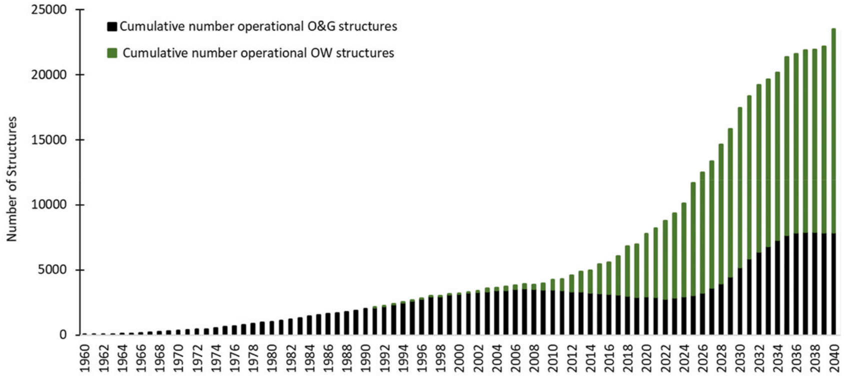
Fig. 2. Current and forecast density and distribution of operational offshore infrastructure (i.e. installed minus decommissioned infrastructure) for combined hydrocarbon and wind generation now – 2021, in 2025, 2030 and 2050. Data sources: Rystad [1], Emodnet [17], BOEM [18] & Geoscience Australia [1]. Cartographic data from ESRI, GEBCO &De Lorme. Increased density most evident offshore North West Europe, China and Japan - largely driven by rising numbers of offshore windfarms. The change in density of ocean infrastructure can be explored interactively via the online map, or dynamically (but not interactively) at the video link https://youtu.be/R6wZMXlz1AU.



(A) Number of offshore projects installed (above the zero line) and decommissioned (below the zero line) globally.



(B) Number of offshore structures installed and decommissioned globally, noting offshore wind projects typically comprise many tens or hundreds of structures while a hydrocarbon project will more typically comprise a single structure.



(C) Total number of operational offshore structures (installations minus decommissions)

Fig. 3. Historical and forecast time series of installation and decommissioning activities for oil and gas (O&G) and offshore wind (OW) (A) number of projects, (B) number of structures, and (C) resulting number of operational structures in our oceans. Oil and gas (O&G) shown in black, offshore wind (OW) shown in green.

be designed, to transform what is currently a liability on the private and public purse and the environment, to an economic, environmental and social asset. We close with considerations on the necessity of balancing the economic, environmental and social aspects when considering marine space planning, sustainable design and end-of-engineered-life management.

4.2. Economic considerations

Decommissioning offshore infrastructure is expensive, and challenging to precisely estimate. Total global offshore decommissioning expenditure has been predicted at US$210 bn over the period 2010 to 2040 [30], and more recently US$42bn from 2020 to 2024 [31], dominated by activity in the UK North Sea, $17bn compared to $5.7 bn in the Gulf of Mexico. While predictions made in the last decade for decommissioning costs in the UK North Sea to 2050 have varied by a factor of 2; £27 bn was predicted in 2010 while the same authority predicted £59 bn and £49 bn in 2017 and 2019 respectively [32,33].

Nearly half of current offshore decommissioning costs are associated with well plugging and abandonment (P&A) [32], which will cease to be an issue for renewables. However, as identified by Figs. 1 and 3, hydrocarbon production is still very much part of the energy mix for the foreseeable future without new economic levers to accelerate the transition to renewable energy. Even with projected reductions in well P&A taken into consideration, the default practice of complete removal remains expensive. Decommissioning activity creates a new economy and with it job creation, or reduction in job losses compared to an economy based on construction and operation (e.g. Ref. [34]), but in many

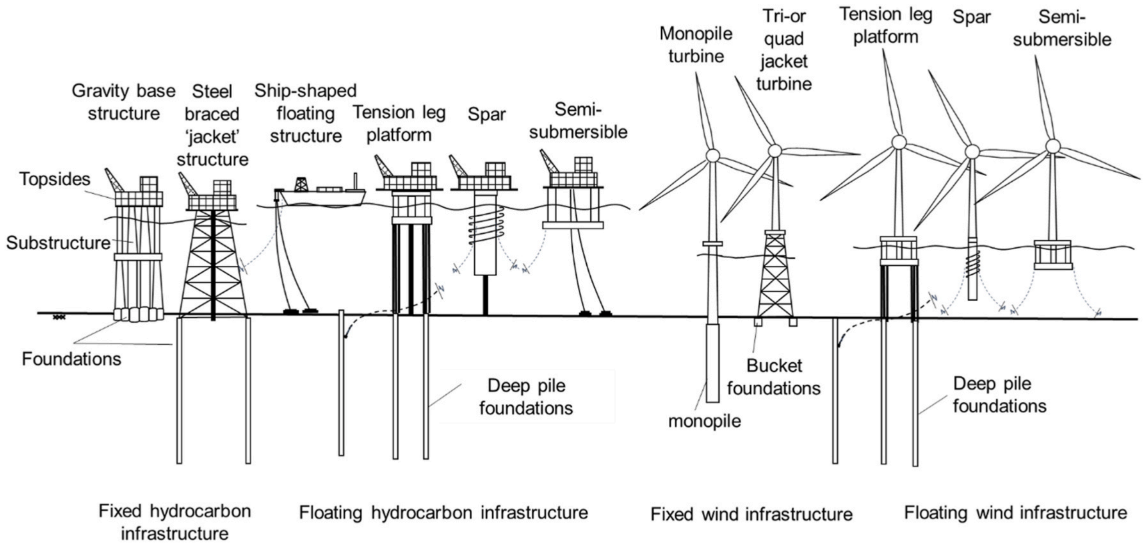


Fig. 4. Examples of offshore infrastructure for hydrocarbon and wind energy.

regions the cost of decommissioning activity is ultimately borne by the tax payer.

Changes in current tax regimes can redistribute where the burden lies, but not the overall cost of the activity. Carbon or embodied energy taxation may initially increase cost of development and decommissioning, but also drive positive investment in alternative technologies to minimize economic cost in the mid to long term. This may include investment in renewables over hydrocarbons, in sustainable, recyclable materials for renewables infrastructure, or in research to create an evidence base for comparative assessment of alternative (potentially less expensive) decommissioning options.

Life-cycle modelling and circular economy principles can refocus the lens of cost and benefit, beyond the direct financial cost/benefits and assist redistribution of weighting of importance of direct and indirect economic costs and benefits, as well as financial value attributed to environmental and social costs and benefits.

Economic models should enable the energy needs of the whole population to be met, without detriment to any particular group or the environment. The Doughnut economic model sets out a framework to operate in 'the safe and just space' where people's needs are met and planetary limits are not exceeded [35].

The challenge then, is how can offshore infrastructure be designed and decommissioned so as to support the economy, environment and social foundation across local to global scales?

4.3. Environmental considerations

Various studies have shown increase in biota and biodiversity around offshore infrastructure (e.g. Refs. [36–38]), particularly in regions where seabeds have been eroded e.g. by trawling, or little natural reef exists. Programs in the North Sea such as INSITE [39] and LINSI [40] provide valuable data sets and the role of offshore infrastructure as habitat for marine biota is a major driving force in the 'rigs-to-reefs' debate [36,41]. Habitats and ecosystems that develop around infrastructure can be damaged or destroyed during removal, even if for relocation, prompting the question whether from an environmental perspective it more rational to leave fixed offshore infrastructure in situ after decommissioning since purpose built artificial reefs are installed globally to serve both recreational and environmental recovery needs. Going further, we can question if operational or decommissioned offshore structures can be engineered or augmented to have a beneficial effect on the environment in which they reside [29].

If in situ decommissioning is to become an option for offshore infrastructure, it is essential to identify the long term effects of leaving infrastructure in place in perpetuity. Offshore infrastructure is designed for a 25 or 50 year design life and extrapolation of material response is uncertain [42–44].

Risk to the environment of contamination by hydrocarbons reduces as the asset base shifts from oil and gas to renewable energy structures, but questions of how structures will break down, into either large or small parts, and how this will affect the environment still need to be understood. As such, the question becomes "is in situ decommissioning 'less' damaging to the environment than removal and disposal onshore?". In turn, this forces us to consider if we are currently capable of accurately quantifying this [45]. Uncertainties about the fate of plastics in the ocean and the extent of the environmental threat provide a topical parallel, albeit plastic in the ocean is an unplanned intervention. We should not assume that current decommissioning methods are environmentally neutral – they are not. Our challenge then is to design a future asset base of renewable energy structures that have minimum – or even beneficial – impact during and at the end-of-engineered-life.

4.4. Social considerations

The above aims directly align with recent calls for an 'energy-just world' [46] where benefits and burdens are equitably shared and communities are directly engaged with energy making decisions. The nature of social opportunities and consequences are more complex to quantify than environmental impact alone. Issues of environmental and economic cost and benefit cross-cut with concepts of identity, access and ethics [47]. As such, assessing opportunities and consequences goes beyond figures of energy production and economic return. The creation of large numbers of structures offshore changes how communities can use and engage with maritime space, what their vistas are and how they relate to the world around them. From the communities that grow up around servicing these structures, to those whose actions and activities are re-shaped by their presence. There is no single or correct response to these issues, they reflect the differing views of diverse stakeholders that need to be considered not only during construction and production, but also at end-of-engineered-life.

Within the literature on energy justice there is a distinct thread addressing issues of 'distributional justice', that resources are not equally available across the globe and benefits do not always accrue at the point of impact [47]. The focus of these discussions have largely been on production phases and economic return, rather than the impact and opportunities of end-of-engineered-life, even when carrying out social life cycle assessment of energy systems (e.g. Ref. [48]). In this light, the drive for the complete removal of structures is understandable, in that it might be seen to lessen the long-term point specific impact on communities and environment, and ensure clear lines of accountability. Current studies do, however, make clear potential routeways for social benefit via decommissioning. The shift to offshore wind within the UK has led to the creation of c. 27,000 jobs up to 2020 [49] and decommissioning stands poised to drive a second round of job creation. Similarly, at a global level, the potential for offshore wind to serve a wider audience is clear. Considering Fig. 1B, it is apparent that large areas, particularly in the global south, could benefit. Up to one third of African coastal states have clear potential, offering a cleaner energy base for economic development [50]. Realising this potential, however, is contingent on continued development of turbines capable of operating in greater water depths, most likely as floating platforms. It is with these floating platforms, and the potential to share technological developments, that the strongest societal gains can be seen. Floating platforms offer the chance to access the most consistent wind resources, do so out of sight of land and offer new possibilities for repurposing and decommissioning.

4.5. Balancing economic, environmental and social considerations

The economic, environmental and social opportunities and consequences of designing and decommissioning offshore infrastructure are deeply inter-related. They cannot be based purely on direct economic considerations or costs, but must also have regard to the environmental consequences, and to the social impact on local stakeholders. That social impact may affect stakeholders' ways of life and identity as much as their capacity to make a living, or enjoy their environment. The fused nature of these interests means that neither economic, environmental nor social considerations can automatically be given universal priority. Even if one could or should trump the others, the calculation of cost-benefit is crude regarding quantification of non-economic values such as health, environment or society more broadly [50]. Further complicating matters, there is a significant temporal dimension to consider: the short term economic, environmental or social costs or benefits might indicate a different approach to consideration of medium or long term consequences.

There is thus no single answer to how marine spatial planning for ocean energy provision, design or end-of-engineered-life of ocean infrastructure should be managed: different locations will require different approaches. But equally, oceans respect no borders - environmental consequences of local decision-making are global. This in turn necessitates an approach that recognises and supports local regulation, framed by internationally agreed principles of decision-making. To achieve such agreement is not easy. Elements of law and regulation exist which address some of the issues raised, and permit for example the repurposing of offshore infrastructure [51] but this is ultimately in the hands of local regulators (e.g. Ref. [52]). While this is being addressed with regard to end-of-engineered-life of the current asset base, it is important to not lose sight of similar considerations which should apply equally to future design.

The convergence of economic, environmental and social costs and consequences in end-of-engineered-life and future design situates this challenge squarely within the ambit of the UN Sustainable Development Goals (SDGs). Explicit recognition of this attaches it to a framework of purpose and commitment which has near universal buy in. Such universality will be crucial to the development of an appropriate global regulatory framework, as both its agreement and application will be dependent upon consensus which has already been expressed in the context of the SDGs.

5. Concluding remarks

This paper quantifies, for the first time, the spatial and temporal distribution of offshore energy infrastructure against a backdrop of offshore energy resources, both hydrocarbon and renewable. The data has been synthesised into a freely available interactive map allowing any user to explore any aspects of the data to enable informed marine spatial planning and innovations in design and decommissioning practices for ocean infrastructure.

In this paper, we have highlighted some insights into type, quantity, density and geographic centres of the accumulating asset base, and identified a shifting loci of offshore activity from the Gulf of Mexico to offshore NW Europe and Asia. We have explored some pertinent economic, environmental and social considerations for development and decommissioning in our oceans, and emphasised the need to balance the economic, environmental and social opportunities and consequences to ensure responsible and sustainable management of our oceans in the transition to ocean renewable energy.

This paper would not have been possible a few years ago, but data on ocean infrastructure is increasingly available and easier to access. This opening up has been driven by implementation of legislation with regard to planning, and also provision of online data repositories, ensuring greater transparency. Access to this data allows us to capture the size and scale of the challenge at a global level, but also to zoom in and consider local impacts. In order to effectively manage this challenge responsibly we need to be able to work at both extremes, from local concerns to global issues.

Author contribution statement

Gourvenec led development of structure and writing of the paper, drafting the text with the exception of the sections on (i) mapping, (ii) social opportunities and consequences and (iii) balancing economic, environmental and social opportunities and consequences. SG contributed to the data analysis and interpretation.

Sturt led the data analysis and created the maps, drafted the text sections on (i) mapping and (ii) social opportunities and consequences, reviewed and provided comments and edits on the whole paper.

Reid drafted the section on 'balancing economic, environmental and social opportunities and consequences', reviewed the paper and provided comments.

Trigos contributed to the section on economic opportunities and consequences, and reviewed the paper.

All authors were part of discussions that shaped the scope of the paper.

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.

Acknowledgements

This project received funding through a Worldwide Universities Network (WUN) Research Development Fund award 'Environmental and social consequences of decommissioning offshore infrastructure'[2]. Susan Gourvenec is supported by the Royal Academy of Engineering under the Chairs in Emerging Technologies Scheme, Fraser Sturt is supported by the award of a Philip Leverhulme Prize.

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