Article:

O'Shea, Ryan, Capuzzo, Elisa, Hemming, Victoria et al. (12 more authors) (2024) Managing offshore multi-use settings:Use of conceptual mapping to reduce uncertainty of co-locating seaweed aquaculture and wind farms. Journal of Environmental Management. 120696. ISSN 0301-4797

https://doi.org/10.1016/j.jenvman.2024.120696

Journal of Environmental Management 358 (2024) 120696

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

Managing offshore multi-use settings: Use of conceptual mapping to reduce uncertainty of co-locating seaweed aquaculture and wind farms

Ryan O'Shea [a,l,*], Elisa Capuzzo [b], Victoria Hemming [c], Gretchen Grebe [d], Rick Stafford [e], Sander W.K. van den Burg [f], Daniel Wood [b], Gordon Watson [g], Victoria Wells [h], Teresa Johnson [i], Stefan Erbs [j], Jaap W. van Hal [k], Bas Binnerts [k], Alexandra M Collins [l], Caroline Howe [l]

[a] *Department of Chemical Engineering, Imperial College London, South Kensington, London, SW7 2AZ, United Kingdom*
[b] *Centre for Environment, Fisheries and Aquaculture Science (CEFAS), Pakefield Rd, Lowesoft, NR 33 0HT, United Kingdom*
[c] *Department of Forest and Conservation Sciences, University of British Columbia, Vancouver, BC, V6T 1Z4, Canada*
[d] *Marine Biological Laboratory, University of Chicago, 7 Mbl St, Woods Hole, MA, 02543, USA*
[e] *Department of Life and Environmental Sciences, University of Bournemouth, Fern Barrow, Poole, BH12 5BB, United Kingdom*
[f] *Wageningen Economic Research, Wageningen University and Research, Droevendaalsesteeg 4, 6708, PB Wageningen, Netherlands*
[g] *School of Biological Sciences, University of Portsmouth, Winston Churchill Ave, Southsea, Portsmouth, PO1 2UP, United Kingdom*
[h] *School for Business and Society, University of York, Church Lane Building, York Science Park, Heslington, York, YO10 5Z, United Kingdom*
[i] *School of Marine Science, University of Maine, 200 Libby Hall, Orono, ME 04469, USA*
[j] *UiO:Energy and Environment, University of Oslo, Gaustadalléen 21, 0349 Oslo, Norway*
[k] *Netherlands Organisation for Applied Scientific Research (TNO), Westerduinweg 3, 1755 LE Petten, The Netherlands*
[l] *Centre for Environmental Policy, Imperial College London, South Kensington, London, SW7 2AZ, United Kingdom*

ARTICLE INFO

Handling editor: Jason Michael Evans

Keywords:
Seaweed aquaculture
Wind farms
Cognitive mapping
Multi-use setting
Delphi
Impact assessment

ABSTRACT

The offshore Multi-use Setting (MUS) is a concept that aims to co-locate marine industrial activities, including wind farms and aquaculture. MUS is considered an innovative approach to promoting efficiency in space and resource use whilst contributing global policy priorities. However, the impacts of MUS development across social, economic, and environmental domains are uncertain, hindering the commercialisation of the concept. In this study, we initially demonstrate the potential consequences of co-locating seaweed aquaculture and a wind farm as a step towards MUS. Using a hypothetical case study and modified Delphi methodology, 14 subject matter experts predicted potential outcomes across social and environmental objectives. Five Cognitive maps and impact tables of 58 potential consequences were generated based on experts' perspective on co-locating seaweed aquaculture and a wind farm. The findings highlight the potential to exasperate pressures in the area, including those already attributed to wind farm operations, such as species mortality and stakeholder conflict. However, it may also enhance social-ecological conditions, such as resource provisioning and promoting habitat functionality in the region, through the addition of seaweed aquaculture. The cognitive maps demonstrate the complexity of managing MUS implementation, where high degree of variability and uncertainty about the outcomes is present. The findings of this study provide the vital entry point to performing further integrative assessment and modelling approaches, such as probabilistic analysis and simulations, in support of MUS decision-making. The research also strongly recommends alternative strategies in the pursuit of combining seaweed production and wind farms to avoid significant financial (among many other) trade-offs and risks. More broadly, we have found that our approach's ability to visually represent a complex situation while considering multiple objectives could be immensely valuable for other bioeconomy innovations or nature-based solutions. It helps mitigate the potential for expensive investments without a comprehensive evaluation of the associated risks and negative impacts, as necessitated by the principles of sustainability in decision-making.

* Corresponding author. 109 Weeks Building, 16-18 Prince's Gardens, London, SW7 1NE, United Kingdom.
E-mail address: ryan.oshea18@imperial.ac.uk (R. O'Shea).

https://doi.org/10.1016/j.jenvman.2024.120696
Received 3 July 2023; Received in revised form 7 March 2024; Accepted 17 March 2024
Available online 12 April 2024

1. Introduction

The production of renewable energy is a priority challenge for societies demonstrated by industrial policies including those of the European Union (EU) and nations globally (European Commission, 2022; International Energy Agency, 2022). Simultaneously, there is growing need for alternative food production and security, where aquaculture of lower trophic groups such as bivalves and seaweed, are of particular interest to policy makers as it does not exacerbate pressures on terrestrial ecosystems typical of agriculture such as land use change, fertiliser usage and coupled carbon emissions alongside depletion of freshwater (Anderson et al., 2017; European Commission, 2021; Garlock et al., 2022). The offshore Multi-use Setting (MUS) refers to the planning and engineering concept of co-locating or co-developing[1] marine industrial activities together including energy infrastructure and aquaculture, and thus is a solution contributing to both food and energy security challenges from the same ocean space (Abhinav et al., 2020; Steins et al., 2021). Wind farms sited in offshore regions i.e. away from land and coastal areas, presents an optimal solution to generate renewable energy with favourable conditions for maximising energy yields(Dincer et al., 2021; Barooni et al., 2022) and bypassing the social barrier of "NIMBYISM", a phrase used to capture the rejection of visually displeasing projects by local residents (Bates and Firestone, 2015; Susskind et al., 2022). However, the fixed structures of wind farms typically result in the exclusion of other marine stakeholders, such as large pelagic fisheries and shipping and carry detrimental impacts to ocean ecology including species mortality and general biological disturbance (Abhinav et al., 2020; Galparsoro et al., 2022). Proponents of MUS advocate that including alternative industries within these zones will mean efficient utilisation of space that would otherwise not be used by other marine stakeholders, thus reducing competition for spatial resource by expanding activities in the burgeoning marine economy (Abhinav et al., 2020). Furthermore, aquaculture and wind farm co-location has been pitched in Europe as a sustainable development pathway with claimed improvements to sustainability including, but are not limited to, marine conservation, economic cost reductions and growth, and enhancing stakeholder rights (Przedrzymirska et al., 2021). Chief among such activities targeted for integration within wind farm array(s) is seaweed production (Buck et al., 2018; van den Burg et al., 2020).

The seaweed sector is being poised for significant growth in European and North American nations with policy initiatives and production increasing year-on-year (Araújo et al., 2021; García-Poza et al., 2020; Hochman and Palatnik, 2022). The bulk of seaweed cultivation is attributed to nearshore and coastal areas using the long line technique whereby seaweed is farmed on a rope-like material extending along a water column, anchored to the seabed, and suspended by buoys (Buschmann et al., 2017; García-Poza et al., 2020). Seaweed aquaculture has been highlighted to promote several benefits to communities including enhancing ecosystem services, such as regulating eutrophication and ocean acidification, forming habitats for marine life, regulating the climate, and provisioning of biomass for human use (Hasselström et al., 2018). Seaweed farming may also be configured adjacent to other lower trophic organisms such as mussel and/or oysters, known as Integrated Multitrophic Aquaculture (IMTA) systems (Buck et al., 2018; Troell et al., 2009). Thereby maximising sequestration potential of inorganic and organic material in the water columns including carbon and nitrogen, concomitantly provisioning different sources of biomass with applications ranging from pharmaceuticals and nutraceuticals to food, feed and fertiliser (Roleda and Hurd, 2019; Torres et al., 2019; van den Burg et al., 2022). However, costs of moving aquaculture offshore to increase production potential are high and stakeholder opposition is still a concern in the marine environment (Buck et al., 2018; Holmer M, 2010). On the other hand, co-locating seaweed aquaculture inside wind farms as a move towards the MUS provides a potential pathway to address some of the implementation issues facing offshore aquaculture. The suggested advantages include minimising potential for marine stakeholder conflict owing to the reduced presence of stakeholders inside wind parks, larger areas available for production offshore and opportunities for cost sharing with wind farm operators (Buck et al., 2018). Moreover, pilot projects have demonstrated the technical feasibility of infrastructure for offshore seaweed production inside a wind farm array but have not yet become standard practice for commercial marine operations (Buck et al., 2017). This is because the full extent of impacts from co-locating seaweed aquaculture and wind farms are uncertain and lack of support for the development of MUS system(s) limits implementation with community support for projects essential to their feasibility (van den Burg et al., 2020). Therefore, greater understanding of the consequences of co-locating seaweed aquaculture and wind farms is needed in addition to decision support tools for evidence-based decision-making and effective planning if MUS systems were to be implemented (Pınarbaşı et al., 2017).

The decision to proceed with co-locating seaweed aquaculture and wind farms as a move towards the MUS has the traits of a complex decision problem (Hemming et al., 2022) with multiple objectives for management to satisfy (Abhinav et al., 2020), uncertainty of outcomes and risk concerns (O'Shea et al., 2022; van den Burg et al., 2020a,b). Managing development would thus benefit from taking a structured decision-making approach (a process of collaborative, facilitated group-deliberation methods to multiple objective decisions) (Gregory et al., 2012) and integrative assessment modelling (IAM) techniques (qualitative and quantitative methods combining social and natural domains) to generate information in support of decision-making that is presently lacking (Abhinav et al., 2020; O'Shea et al., 2022). To successfully initiate IAM approaches in understanding outcomes of co-locating seaweed aquaculture and wind farms, conceptual maps, or models, are a key requirement (Burgman et al., 2021; French, 2021; O'Shea et al., 2022). However, to successfully achieve this task, previous attempts of conceptual mapping in the MUS topic recommend the use of diverse, expert groups to address uncertainty and adequately evaluate the complex interactions that may result from development(s) (O'Shea et al., 2022).

Group cognitive modelling is a technique that diagrams the mental representation of a selected group of people using a facilitated process to promote understanding about a complex situation (Burgman et al., 2021). The procedure brings together diverse knowledge domains (natural to social) and significantly improves the accuracy of representing a situation owing to structured protocols and value of collective intelligence (Burgman et al., 2021; Franco and Montibeller, 2010; Vercammen and Burgman, 2019). Moreover, the resulting model frameworks provide the fundamental entry point needed to promote integrative analytical techniques such as Coupled Component Models (CCM), Bayesian Network (BN), System Dynamics and so on, that supports decision-making under uncertainty within complex environmental projects and contexts (Burgman et al., 2021; French, 2021; Kelly et al., 2013; Luna-Reyes and Andersen, 2003). For example, group conceptual models have been designed to better understand the drivers of forest flammability and risks, demonstrating the importance of structuring diverse perspectives in model creation (Cawson et al., 2020) or creating system dynamic models to support marine spatial planning in South Africa (Vermeulen-Miltz et al., 2023). In parallel, the use of subject matter expert judgement has long been applied to the decision-making process for questions dealing with uncertainty, i.e., those lacking data or information, on a variety of topics ranging from environmental management to security and defence (Beaudrie et al., 2011; Martin et al., 2012). A well-used method for structured expert group elicitation is the Delphi method. The Delphi method was invented by the RAND

[1] Co-development offers a step up from co-location whereby multiple activities are designed to operate together at the planning and engineering stage. Co-location refers to the addition of activities to an already existing and separate.

corporation (Dalkey and Helmer, 1963) and describes the systematic process used in management research of selecting and interviewing subject matter experts to produce information against defined objective (s) whilst mitigating for known limitations in expert elicitation (Brady, 2015). The Delphi method allows researchers to access knowledge using a proven structured elicitation process. Furthermore, the Delphi method ensures that anonymity may also be kept among the participants as part of the process, preventing issues such as "group think" whereby participants may not express full opinions or conform to the group opinion (Brady, 2015).

The MUS systems are innovative and developing aquaculture could support the industrial concept of "Sustainable and/or Circular Bioeconomy" (SCB). The SCB is the combination of biotechnological, bioprocessing and general scientific knowledge within the political objective of using current and further biological resources in a "sustainable and economic way" (Aguilar et al., 2019). However, as the purpose of the SCB is to promote sustainable development, otherwise defined as sustainability, any activity falling within its remit must contribute to this objective, such as advancing the United Nations (UN) Sustainable Development Goals (SDGs) in that environmental, social and economic conditions are holistically improved (United Nations, 2015). Without further understanding of the potential consequences across social and environmental domains of co-locating seaweed aquaculture and wind farms as a move towards the MUS, progressing implementation of the concept is unlikely and may result in delay, or loss, of the innovation proposal and with it, possible resource benefits. Therefore, the aim of this study was to explore the potential consequences of co-locating seaweed aquaculture and wind farms. A sub-objective of this assessment was to then structure information about the potential consequences, primarily in the form of conceptual maps, to support decision-making under uncertainty and facilitate IAM and decision support tools for sustainable management of seaweed-wind farm MUS. In this paper we present a hypothetical case study for a MUS to provide system boundaries for assessing the system and explore this case-study using group cognitive modelling technique to evaluate and diagram the potential consequences of its implementation across social, economic, and environmental objectives.

2. Methodology

2.1. Hypothetical multi-use setting case study: developing seaweed aquaculture inside Hornsea wind farm

Due to limited information from real-world case studies and the absence of routine commercial operations at scale, a hypothetical scenario was proposed to establish a context for performing cognitive modelling of co-locating seaweed aquaculture and wind farms. This allowed us to define social and ecological variables and spatial and temporal system boundaries as required for the assessment (Hodgson et al., 2019). Improving on previous assessments where scenarios contained no boundaries and largely generalised MUS systems (Abhinav et al., 2020; Buck et al., 2018). The North Sea territory formed the basis of the hypothetical case study, containing several offshore wind farms that range from those in concept/early planning stages to operational or decommissioned wind parks (Fig. 1) (Chirosca et al., 2022) with significant competition for ocean space among marine industries (Pettersen et al., 2023).

The subsequent information was compiled into a PDF document and sent to participants to aid the conceptual mapping process for the assessment. A schematic was included to clarify the specific components of interest to the assessment (Fig. 2).

2.1.1. Wind farm location

Hornsea Projects 1 and 2 are existing wind farms and were used for a hypothetical scenario of installing seaweed farms. This was based on the suitability of cultivating Laminarian (a genus of brown seaweed) species

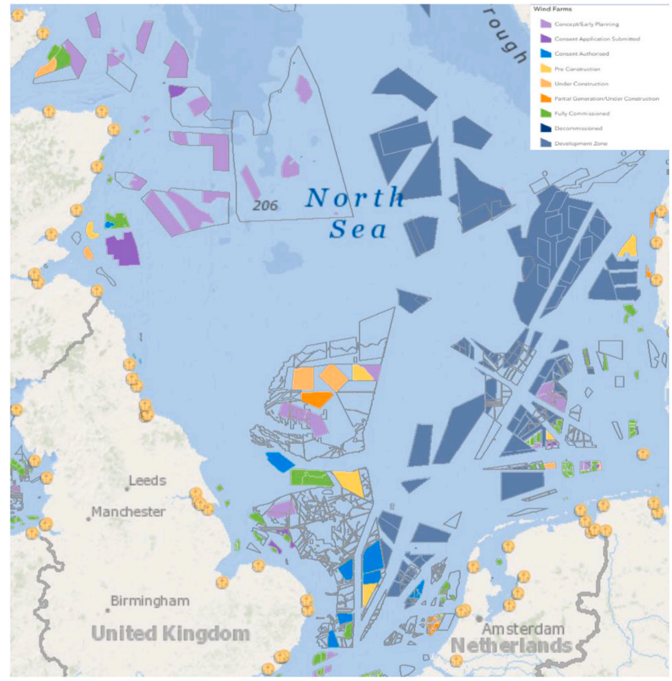

Fig. 1. Map of wind farm projects including active, planned and decommissioned within the North Sea (https://map.4coffshore.com/offshorewind/) (TGS 4Coffshore, 2024).

in this region (Marine Management Organisation, 2019), successful pilot tests of installations of seaweed farms in neighbouring regions to the United Kingdom (UK) (Buck et al., 2017) and it has one of the largest commissioned wind farms in the area; namely, Hornsea Project One (Ørsted, 2020). Hornsea Project 1 is the first stage of four total developments and was commissioned for operation in 2020 (Ørsted, 2020). The site location is approximately 65 km off the coast of the Yorkshire County (Ørsted, 2020) and Table 1 summarises the Hornsea wind farm development including dates the projects are operational, total number of turbines per project, the size of project zones and the total area the Hornsea wind farm is planned to cover. In our hypothetical case-study we proposed that seaweed aquaculture would be developed inside the wind farm array, starting in 2021 and occupying 1% of the total available area (869.19 km^2) and increasing in size over the next ten years to reach 100% of the wind farm boundary.

2.1.2. Seaweed aquaculture installation

Developing suitable infrastructure and practices for cultivating seaweed in offshore environments is an ongoing research priority to enable offshore production of seaweed. Germany has been performing offshore seaweed aquaculture trials since the 1990s (Buck et al., 2017). Based on experimental studies of three aquaculture designs, a 5-m diameter ring shaped rig device, comprising of an anchor point, metallic components, 80–100 m of rope culture line and a central buoy-was shown to be the most successful at operating offshore in the German North Sea zone and so this was used in the hypothetical case study. Illustrations and images of the rig design used in the study can be seen in Fig. 3 of Buck and Buchholz (2004).

The report by Buck et al. (2017) also discusses successful offshore cultivation of seaweed in Norway, using a device known as the "Seaweed Carrier" and is identified as one of the first contemporary installations in Norway capable of seaweed production on an "industrial scale", however, the report does not fully disclose the materials used in this installation and patent links appeared broken. Nonetheless, the Seaweed Carrier device is briefly explained in Bak et al. (2020) as a "sheet-like structure with free moving cables and single mooring" with "flexible

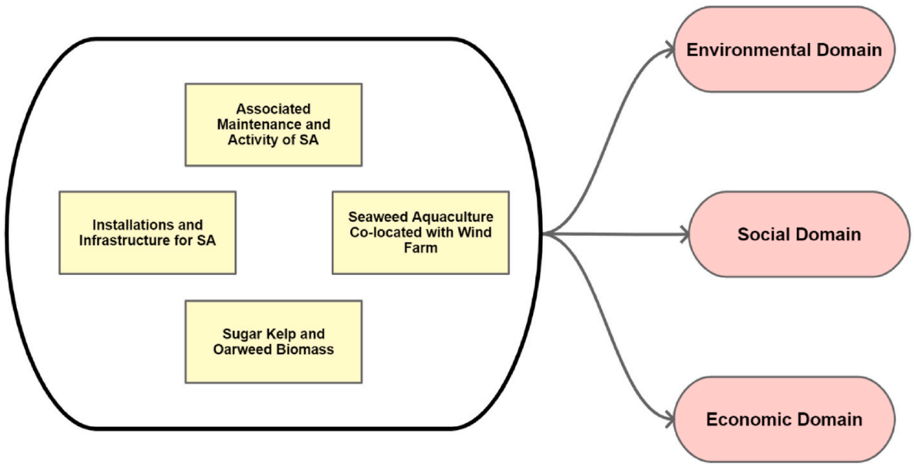

Fig. 2. Schematic outlining the concepts that are the focus of the Delphi panel interviews and direction of impacts being explored to objective categories. SA = seaweed aquaculture.

Table 1
Hornsea wind farm development broken down into respective stages of the project (1–4) with date of operation, individual project sizes and total area (Ørsted, 2020).

Hornsea Project stage	Operation date	Total No. of Turbines	Size (km^2)	Total Area (km^2)
1	2020	174	407.30	2412.98
2	2022	165	461.89	
3	N/A	up to 231	695.83	
4	N/A	up to 180	847.96	

hybrid long-line 6.5 m long and 5 m deep". The installations provided were illustrations of potential structures participants could use to assist with visualising and investigating the hypothetical scenario. See figure 2.7 of Buck et al. (2017), and figure 2 of Bak et al. (2020), for referenced imagery.

2.1.3. Species

A report by the Marine Management Organisation (MMO) (2019) evaluated the potential sites for aquaculture around the UK, including cultivation of seaweed. The report identified that two main species; namely, Sugar Kelp (*Saccharina latissima)* and Oarweed (*Laminaria digitata*), are suitable for farming in above 50% of the UK's Shoreline (Marine Management Organisation, 2019), especially, extending along and off the east coast of England and Scotland (Fig. 3).

In line with this, Buck et al.'s (2017) report indicates that seaweed species deemed most suitable for offshore conditions in European case studies are predominantly associated with the Laminarian genus, including *Saccharina latissima* and *Laminaria digitata*. Although the report occasionally mentions species from different genera, their discussion is comparatively less extensive. Notably, the species chosen for

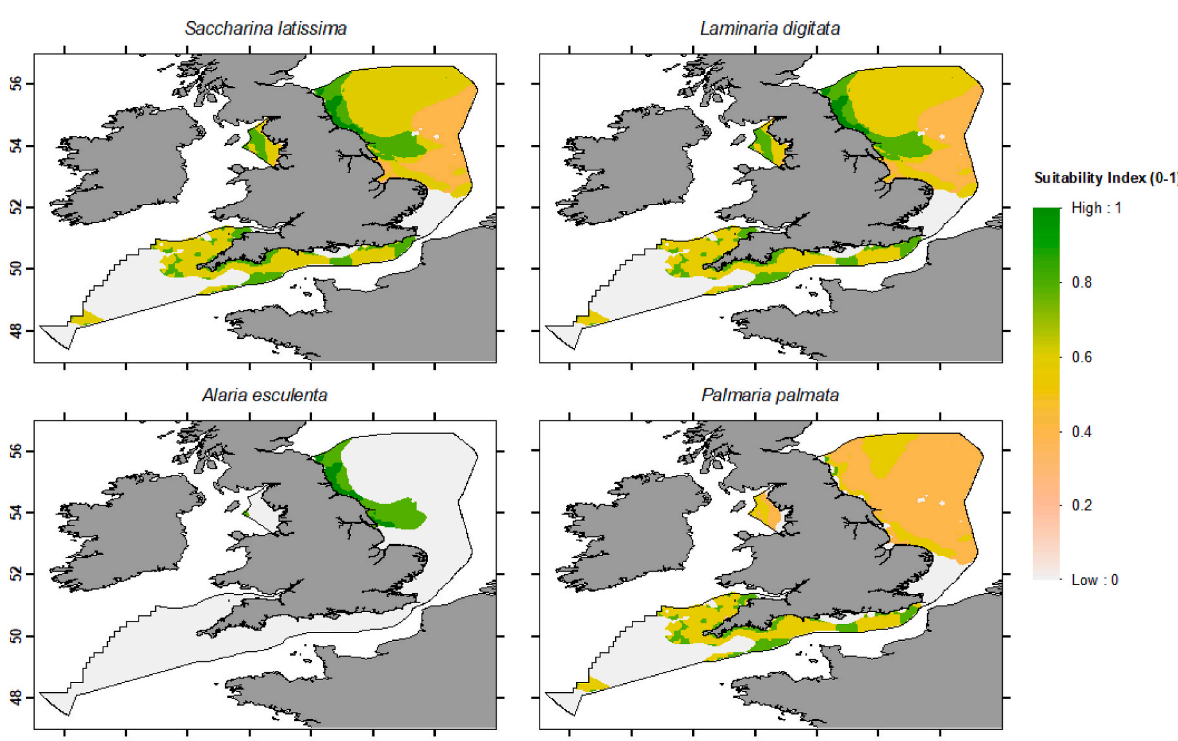

Fig. 3. Seaweed cultivation suitability maps extracted from MMO (2019).

cultivation in our hypothetical scenario are Sugar Kelp (*Saccharina latissima*) and Oarweed (*Laminaria digitata*).

2.2. Conceptual mapping process

The purpose of the group cognitive modelling for this study was to elicit qualitative cognitive models of the potential impacts - environmental, social and economic – associated with the co-locating seaweed aquaculture and a wind farm. The group cognitive modelling process was performed using a modified Delphi method following the guidelines outlined in Okoli and Pawlowski (2004) and Brady (2015), in addition to recommendations on the expert elicitation process made in Page (2008) and Hemming et al. (2018). Multiple steps (discussed below) were used, initiating with the recruitment of subject matter experts (SMEx) between June 2021 and November 2021. An elicitation process followed the recruitment, using surveys and structured interviews to elicit individual mental models, collate available evidence and subsequently, aggregate cognitive models into shared cognitive models for the perceived consequences of the hypothetical scenario proposed for this assessment (outlined in section 2.1). The elicitation process ended by April 2022.

2.2.1. Participant recruitment and group organisation

Subject matter experts were first selected and recruited using a knowledge resource worksheet (a spreadsheet of the required expertise needed for a Delphi study) as described by Okoli and Pawlowski (2004) to help guide the recruitment process. A table of the knowledge criterion used to guide the search, evaluation and recruitment of subject matter experts can be found in Table 2. Participants were grouped based on their assumed expertise drawn from personal webpages, place of employment and publications, into different sub-disciplines and placed into broadly defined categories of environmental or social domains. The target size of the total group was between 10 and 20 participants as recommended by Hemming et al. (2018a,b). The subject matter experts were recruited from a mix of organisations including academic, non-governmental organisation and business. The selection process was guided by a relevant knowledge criterion for the study whereby disciplines and areas of experiences relevant to the offshore MUS were first defined and then used to search and evaluate potential SMEx for recruitment.

Table 2
Relevant knowledge criterion used to guide the search, evaluation, and recruitment of subject matter experts relevant to the social, economic including technology and environmental domains relating to seaweed aquaculture development inside a wind farm.

Domain	Relevant Knowledge/Experience	Type of Organisations
Environment and Technology	Oceanography including chemical, physical and geological Marine biology and ecology including conservation and sustainability Aquaculture including extractive species Materials and engineering Marine biotechnology and bioprocessing Food science and technology Wind farm infrastructure	-Academic -Executive agency of government -non-governmental organisation/Charity -Industry/Business
Social and Economic	Policy and law including marine management and environmental planning Anthropology including coastal and marine communities, democracy and behaviour Renewable energy including wind farm operations Markets and supply chains including biofuel, fertiliser, food, feed, pharmaceutical, cosmetic and nutraceutical Microeconomics and industrial organisation including biotechnology, business development Rural development Biophysical/ecological economics	

A list of SMEx in each knowledge domain (social, engineering, technology and environmental) was created alongside their contact details. Ethical approval was obtained from Imperial College London's Ethics committee (reference number: 21IC6728 SETREC HOD_RGIT). Participants were selected and invited to the study using the contact information provided by their institutions and organisations in addition to recommendations and snowballing by peers. The facilitator (lead author, RO) attempted to create diversity in the design of the final group using variation in "age, gender, cultural background, life experience, education and specialisation"- as these are indicators of intellectual diversity and can provide access to different mental models (Hemming et al., 2018a,b; Page, 2008). The SMEx were approached via email and informed about the study including the hypothetical scenario, aims, objectives and the methodology being used. Ethical consent was sought from respondents willing to join the study. SMEx that agreed to take part were communicated with on an individual basis via telecommunications or email and given a unique code (SK.SA(n)) to keep anonymity among the participants during the study-aiming to mitigate the effects of group settings including "group think" whereby individuals conform to the group consensus and hesitate to express true opinions (Brady, 2015).

Recruitment of participants was attempted from the Americas, Europe and Asia where aquaculture is predominantly practiced and programmes for offshore installations are underway (Froehlich et al., 2017; García-Poza et al., 2020). A total of 62 experts were invited to participate in the study. Of the 61 contacted, 14 final participants took part in the study roughly split between social including economic and technology, and environmental domains of knowledge. Final participants were largely based in Europe with minorities from North America and international backgrounds. The professional background of final participants included research, business (marine energy, seaweed farming and consultancy), governmental and non-governmental (NGO) (think tank and research institute). Junior to senior level positions in organisations were reflected in the final Delphi panel. Table 3 shows the summary statistics of expert participants in the Delphi-cognitive mapping study.

2.2.2. Individual cognitive model development (round 1–2)

Individual consultation via telecommunication, including email and Microsoft Teams, was conducted starting in September 2021 and lasting up to an average of 1.5 h per consultation. Individuals were requested to review the material provided by the facilitator (RO), including the hypothetical scenario (see supplementary material titled: "UK MUS Hypothetical Scenario.pdf) and a list of questions for the study (Box 1). Subject matter experts were given up to 1 month to investigate the topic and provide responses to the questions via a survey sheet akin to a horizon scan (Sutherland and Woodroof, 2009).

The completed survey provided by the experts detailed their perceived impacts of the hypothetical scenario based on the questions/objectives supplied by the facilitator. The survey responses were reviewed by the facilitator and used to propose a preliminary cognitive model using Vensim software (Vensim, n.d), for the purpose of assisting experts to visualise the intended format of the qualitative model structure. The initial responses were also used to create a structured interview format that included a set of semi-open questions divided by each objective-social, economic, and environmental- and response given to their survey, to guide the interview process of a particular expert and their knowledge on the topic. After completing an interview, cognitive model(s) were proposed by the researchers based on the findings of the survey and interview and sent back to the expert for consent that the cognitive model proposed by the facilitator reflects their perspective on

Table.3
Summary statistics of the final experts that participated in the Delphi-cognitive mapping study.

Location	Participants	Background	Participants	Expertise	Participants
Europe	10	Research	8	Social	4
North America	2	Business	2	Economic	5
International[a]	2	NGO	3	Environmental	5
		Government	1		

[a] International was categorised for participants operating in multiple countries.

Box 1
Survey questions for participants.

1) Please list the consequences (positive and or negative) you believe the scenario will have on biodiversity.
   I. If possible, please indicate the species, ecosystems that you believe will be altered and whether they will respond positively or negatively. If you have any information or prior examples we could obtain to support this assessment please note this for us.
2) Please list the consequences (positive and or negative) you believe the scenario will have on ecosystem processes and functions.
   I. If possible, please indicate the process or function that you believe will be altered and whether this has positive or negative implications. If you have any information or prior examples we could obtain to support this assessment please note this for us.
3) Please list the consequences (positive and or negative) you believe the scenario will have on marine resources used by relevant stakeholders.
   I. If possible, please indicate the marine resources altered, the stakeholders you believe will be affected, and whether they will respond positively or negatively. If you have any information or prior examples we could obtain to support this assessment please note this for us.
4) Please list the consequences (positive and or negative) you believe the scenario will have on societal community members and networks.
   I. If possible, please indicate the community members and networks that you believe will be altered and whether they will respond positively or negatively. If you have any information or prior examples we could obtain to support this assessment please note this for us.
5) Please list the consequences (positive and or negative) you believe the scenario will have on economic development.
   I. If possible, please indicate the economic sectors or industries that you believe will be altered and whether this has positive or negative implications. If you have any information or prior examples we could obtain to support this assessment please note this for us.

the hypothetical scenario and questions (Box 1). Cognitive models were proposed based on descriptions presented by panellists which could be a single cognitive model for a given area e.g. social impacts, or several cognitive models for broader descriptions resulting from interdisciplinary backgrounds. E.g. social and environmental. All model designs were created and managed by the facilitator to prevent interference or unapproved changes to the cognitive models during the study, however, experts' approval was sought at each stage to edit the facilitator's proposed model, confirming the proposed models reflected their views and prevent errors made by the facilitator.

2.2.3. Shared cognitive model development (round 3)

After all 14 expert interviews were completed and proposed individual cognitive models for each expert were developed, a "standardisation and integration" step was carried out to create a shared cognitive model. The facilitation process for this was broadly adapted from the description of facilitated modelling techniques common to operations research where participants were asked clarifying questions in order to describe and discuss their perspective on the development of a shared cognitive model (Burgman et al., 2021; Franco and Montibeller, 2010). However, all dialogue was conducted using telecommunications-only owing to the UK Coronavirus restrictions and face-to-face interactions were not possible. The aim of this step was to collate information sourced during the study including individual cognitive models and relevant evidence, to propose a shared model output from the expert group to facilitate further analysis and discussion between the group - as recommended in Brady (2015) and Mukherjee et al. (2015). The purpose of the standardisation step was to normalise the terms and explanations used by the different experts. For example, there were language differences, such as the terms used to explain an impact, alongside the level of detail provided by different experts to describe the similar impacts. The individual cognitive models were reviewed to propose impact tables separated into environmental, social and economic objectives by the facilitator (RO). Impacts were further divided into sub-groups suggested by the facilitator and agreed upon by the Delphi panel group, based on emergent properties of individual maps (Eden, 2004). The impact subgroups were based on analysing the category-social, economic or environment-in which the final effect was described i.e. largely affecting social communities (social domain), economic activity (economic domain) and/or marine ecosystems (environmental domain) (Fig. 4).

The impact tables were then used to integrate the cognitive maps to develop a shared cognitive model of the 14 experts about the hypothetical scenario and designated study questions. The experts were asked to review the standardised and collated map and asked to answer the following question:

> *"Do you agree/disagree the standardised and shared model proposals made by the facilitator (RO) have included your original contributions including survey response and individual cognitive model, to the questions posed during this* study*?"*

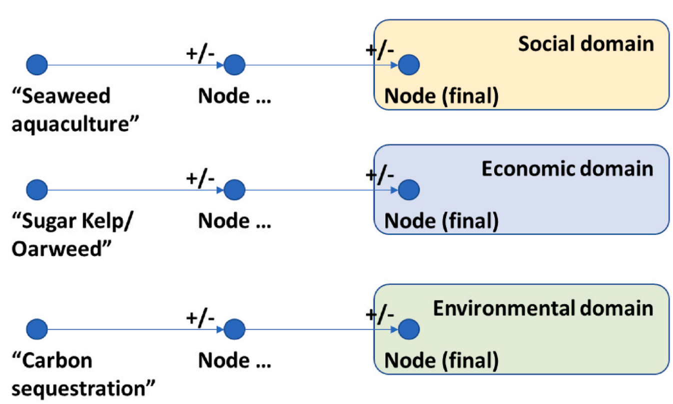

Fig. 4. Schematic illustrating the process of categorising impacts into themes based on the domain of the final impact/nodal change e.g. largely affecting marine wildlife, wind farm infrastructure and so on.

"Do you strongly disagree with any potential consequences proposed by other collaborators? Yes or No- if yes, please provide an evidence source to substantiate your claim."

Clarifying the shared model was to prevent errors and interference with the experts' beliefs owing to the subjective interpretation of the findings by the facilitator (RO). Any disagreement expressed was subsequently followed up to clarify and revise a particular pathway. Experts were also given a chance to provide comments on the collated findings and shared model including whether they disagreed with impacts identified by other experts-based on providing evidence to substantiate their claim and explaining their disagreement. Any information contesting impacts was captured and provided in the results as a form of discussion needed for completing the full Delphi procedure (Brady, 2015). The final revisions and any contested variables were captured via email between the facilitator and SMEx in addition to Microsoft Teams, lasting up to 60 min of call time, between the months of April 2022 and ending in April 2023. The key steps to the group cognitive modelling process and outputs at each stage are summarised in Fig. 5.

3. Results

3.1. Group cognitive modelling

The panel of 14 subject matter experts were convened which resulted in 29 individual cognitive models being captured. Separate models were proposed by an individual SMEx based their breadth/depth of knowledge relating to the objectives of interest (see Box 1). Of the 29 individual cognitive models, 13 related to largely environmental impacts and 16 were largely related to social including economic impacts. The 29 individual models were integrated into five shared cognitive models by the facilitator and accepted by the SMEx panel explaining the perceived consequences of establishing the hypothetical scenario for seaweed farming in Hornsea wind farm across economic, social and environmental objectives over the next ten years. Impact tables were produced providing a list of the suggested consequences alongside an explanation for their causality. Impacts were categorised by objectives -environmental, economic, and societal - and sub-themes within each objective considered emergent themes of the assessment namely, abiotic and biotic (environmental domain), economic and industry development and marine economic stakeholders (economic domain), and social community and infrastructure (social domain). The impact tables can be found in supplementary materials titled ""impact tables (standardised)" and are strongly recommended to be reviewed in combination with the cognitive maps in the following sub-sections for clarity regarding impacts and explanations of causal pathways.

3.1.1. Social to environmental consequences

The "Abiotic map" collates all the perceived final impacts to the non-living components of the ecological system (Fig. 6). Several factors were perceived to influence different parts of the abiotic environment including the seabed and chemical composition of the sea with resulting knock-on effects resulting in perceived impacts to the ocean-atmosphere dynamic. Most impacts had single causal pathways, but in some cases, possible compounding effects were identified, for example, increased rates of seabed sedimentation via two separate causal pathways and increases in (fossil-based) energy demand and consumption due to seaweed aquaculture industry development and disruptions to the operations of the offshore wind farm (Fig. 6). Moreover, the abiotic model included trade-off events, in the case of the climate change variable defined as "Global Warming Potential", the variable may increase or decrease because of the introduction of seaweed aquaculture inside the wind farm array based on the disruptive effect to wind farm operations and seaweed industry development or added carbon dioxide (CO_2) sequestration started by the seaweed biomass at the site.

The "Biotic map", describes the perceived interlinkages between the seaweed aquaculture development and final consequences to the living components of the ecological system (Fig. 7). The perceived impacts have potential effects occurring at the genetic level, microorganismal level including virus and bacterial changes in addition to the interactions with microalgal populations through to larger pelagic organisms and whole ecosystem ecology level. Both aquatic and non-aquatic species including avian organisms, were anticipated to experience impacts. The map highlights a diversity of complex interactions including feedback loops that positively increase variables relating to biodiversity dynamics including, increased predation opportunities and the attraction and/or abundance of biodiversity at the site, in addition to increased habitat complexity (Fig. 7). Trade-offs were present, with primary production suggested to both increase and or decrease depending on the sequence of events (sub-impacts/nodal changes) evolving from the seaweed farm infrastructure and farmed seaweed biomass in addition to the growth and loss of epifaunal species from the area. Compounding effects were also captured on several occasions relating to biosecurity risks with augmentation to marine bacteria and viruses and further amplified with the introduction of non-native species. Further compounding effects may potentially result for aquatic biodiversity amplifying or decreasing the abundance internal and external to the site. The "Economic and Industry Development" map focuses on the perceived implications towards economic activity in the

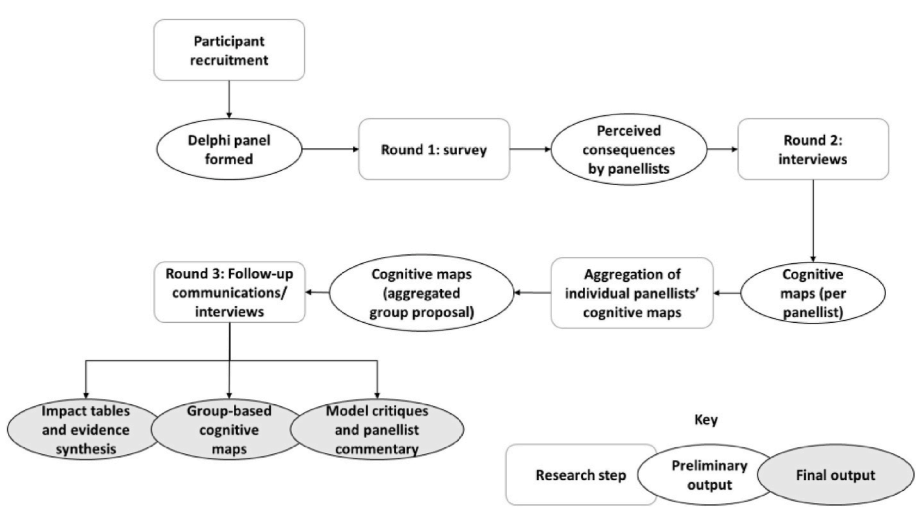

Fig. 5. Workflow detailing the stages of the Delphi and Cognitive mapping processes to identify potential consequences in the environmental, social, and economic domains resulting from hypothetical development of seaweed aquaculture inside Hornsea wind farm.

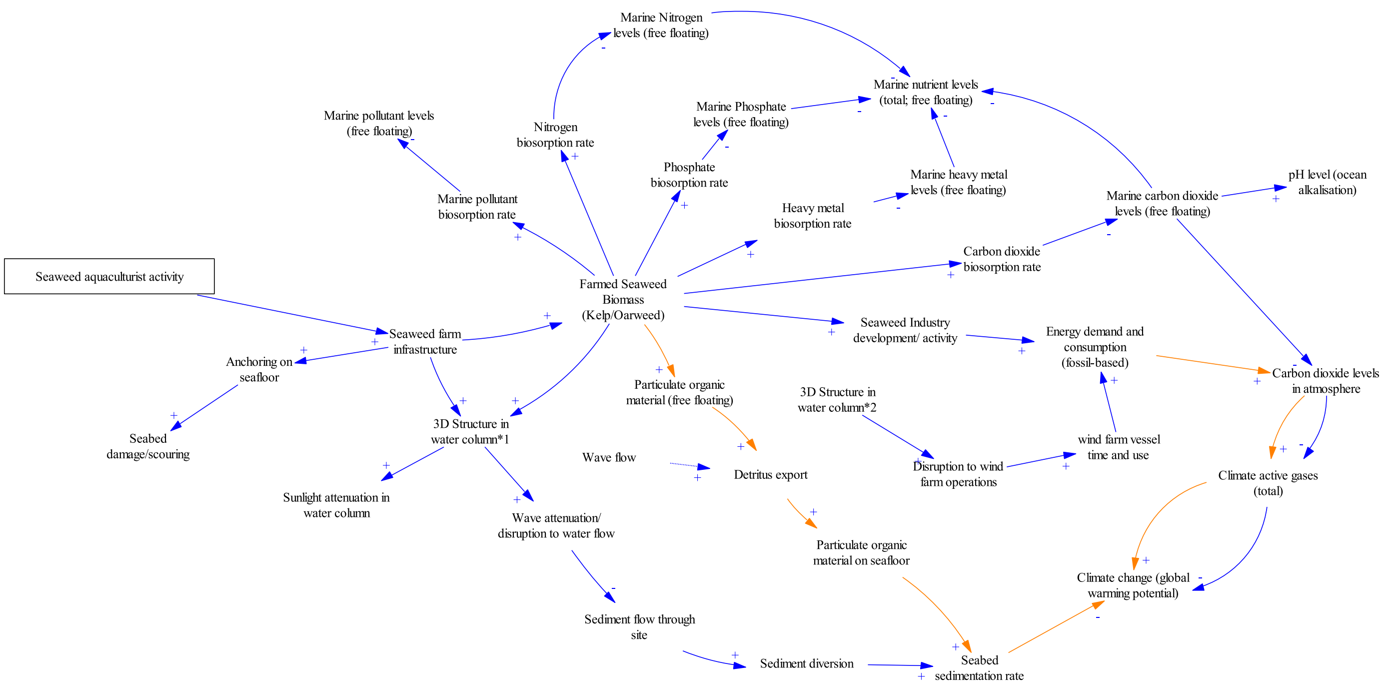

Fig. 6. Standardised and shared cognitive model on the potential impacts to environmental (abiotic) system of the hypothetical scenario of expanding seaweed aquaculture inside Hornsea Wind Farm over the next ten years. -Boxed variable indicates starting node; Arrows show direction of influence between proposed variables (blue for primary and orange for additional/secondary pathways suggested by experts); Dashed lines explain key exogenous variables expressed by participant; plus/minus symbols denote the direction of change i.e. increasing or decreasing, of child nodes. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

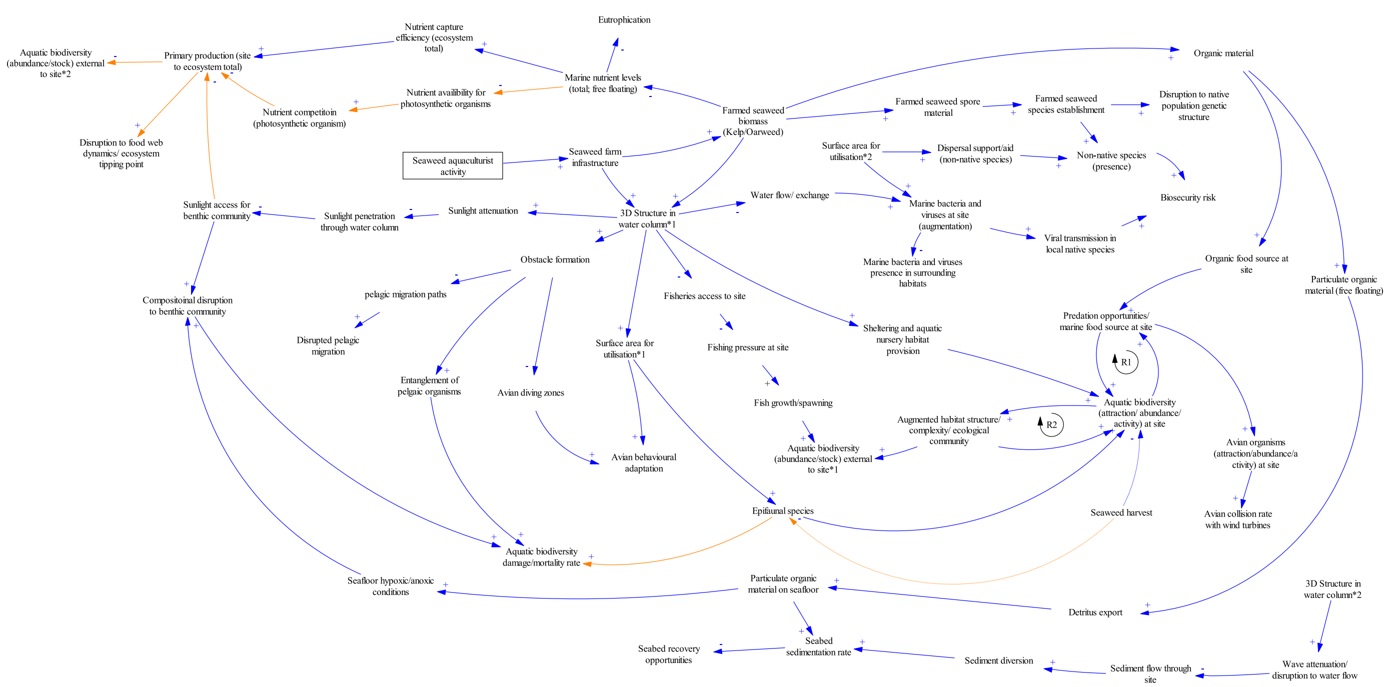

Fig. 7. Standardised and shared cognitive model on the potential impacts to environmental (biotic) system of the hypothetical scenario of expanding seaweed aquaculture inside Hornsea Wind Farm over the next ten years. -Boxed variable indicates starting node; Arrows show direction of influence between proposed variables (blue for primary and orange for additional/secondary pathways suggested by experts); Dashed lines explain key exogenous variables impacting the seaweed farm system; plus/minus symbols denote the direction of change i.e. increasing or decreasing, of child nodes; Rn highlights reinforcing feedback loo; *n indicates secondary or tertiary impacts to/from a node. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

area resulting from the introduction of seaweed aquaculture into the wind farm array (Fig. 8). Several interlinkages with the economic system were expressed with potential for increases in business activity and supply of bio-based products in addition to changes in labour dynamics and innovation resulting from multiple components of the seaweed aquaculture development including presence of seaweed biomass for

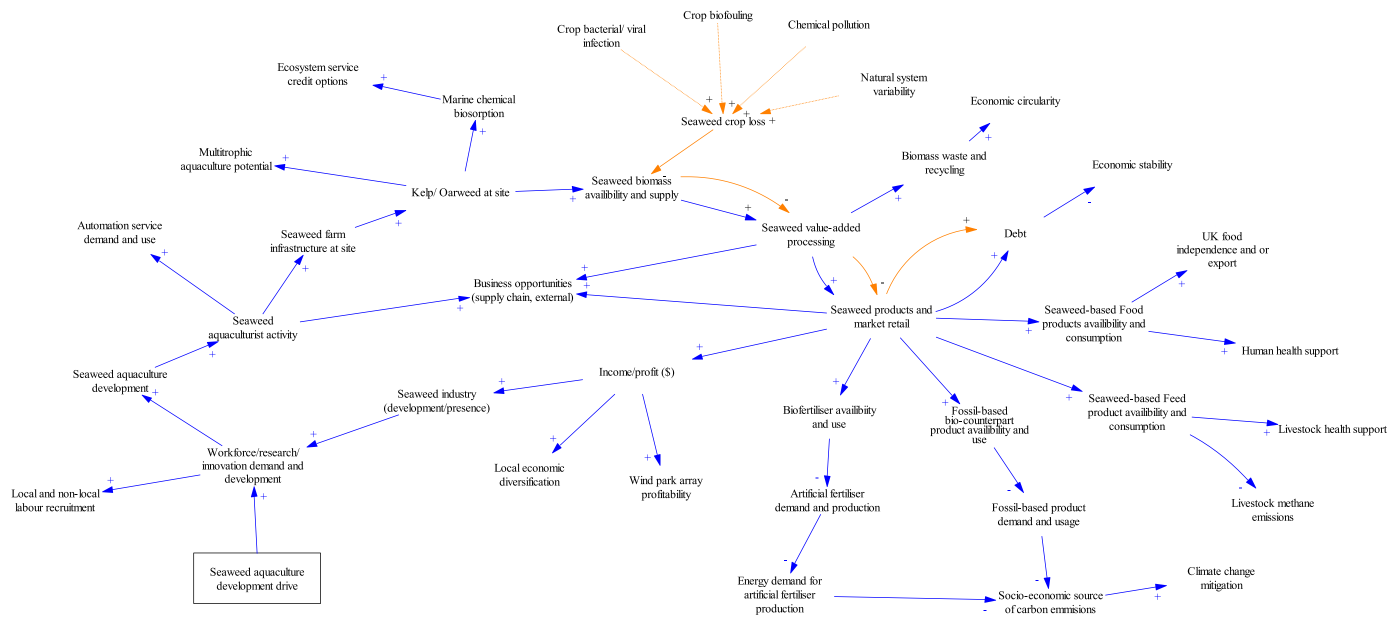

Fig. 8. Standardised and shared cognitive model on the potential impacts to social system (economic and industry development) of the hypothetical scenario of expanding seaweed aquaculture inside Hornsea Wind Farm over the next ten years. -Boxed variable indicates starting node; Arrows show direction of influence between proposed variables (blue for primary and orange for additional/secondary pathways suggested by experts); Dashed lines explain key exogenous variables impacting the seaweed farm system; plus/minus symbols denote the direction of change i.e. increasing or decreasing, of child node; *n indicates secondary or tertiary impacts to/from a node. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

value added extraction, new biomass production and microeconomic activity in the area.

The "marine economic stakeholders" map details the perceived consequences to stakeholders from utilising oceanic resources for commercial purposes (Fig. 9). Multiple existing stakeholders were perceived to be affected by the seaweed aquaculture development including the

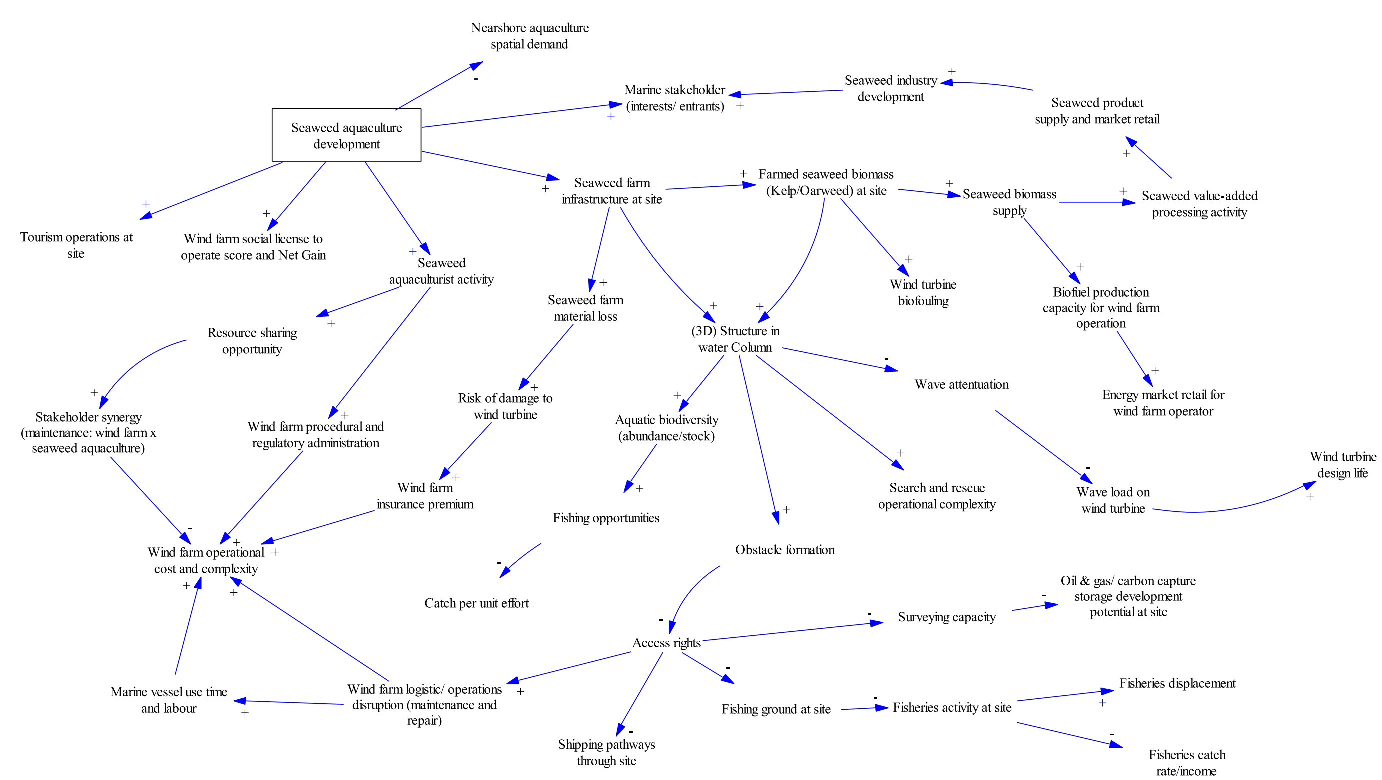

Fig. 9. Standardised and shared cognitive model on the potential impacts to social system (Marine Economic Stakeholders) of the hypothetical scenario of expanding seaweed aquaculture inside Hornsea Wind Farm over the next ten years. -Boxed variable indicates starting node; Arrows show direction of influence between proposed variables (blue for primary and orange for additional/secondary pathways suggested by experts); Dashed lines explain key exogenous variables impacting the seaweed farm system; plus/minus symbols denote the direction of change i.e. increasing or decreasing, of child nodes. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

offshore wind farm, oil and gas/carbon capture storage organisation(s), shipping, tourism sector and fisheries. Trade-off events were highlighted including both possible increases to, and decreases in, the wind farm's operational costs and complexity via multiple causal pathways, owing to the seaweed aquaculture development.

The "Social community and Infrastructure" map presents the perceived impacts relating to the local community and infrastructure, with predominantly non-economic implications (Fig. 10). Different aspects of the local community were affected ranging from the local authority, for example raising administrative needs, or increased pressures on infrastructure and developments in the area. A variety of knock-on effects were expressed in the shared cognitive map with positive feedback loops being present in the case of seaweed aquaculture development increasing local government planning and regulation development because of increased risk and liabilities to the wind farm area from seaweed aquaculture operations. Moreover, the increased availability of seaweed biomass was perceived to enable seaweed value-added process activity that would encourage development of seaweed processing facilities (Fig. 10). Compounding effects were present in the social community map, with multiple causal impacts including lowering the aesthetic value of the area and raising stakeholder conflicts and industry opposition.

The cognitive maps in addition to iterative surveying also produced a catalogue of the suggested impacts with descriptions of the cause(s) for impacts to social, economic and ecological systems-see supplementary materials ("impact tables (standardised).exl"). The impact tables contained available evidence sources and the identifiers of the proposed variables, with multiple identifiers to several variables expressed and in other cases, only containing one-a condense summary of the impact table is found below (Table 4).

3.1.2. SMEx's model evaluation

During the final round of elicitation Subject Matter Experts were provided with the opportunity to contest and comment on claims made by other panellist with opportunities to supply evidence to support their claim. Table 5 captures commentary of panel members contesting specific claims with the likelihood of five impacts being contested/disagreed by panels members and thus, controversial. The main impacts proposed and had their likelihood or accuracy contested were the expectation for non-local or temporary work force extending from the seaweed farm leading to a decrease in income to the local area. The reduction in livestock emissions from consumption of seaweed-based products. Resource sharing opportunities with bioenergy product potentials and reduced operational costs for offshore wind farm. The improvements to human and livestock health and lastly, increased economic circularity capacity and activity.

4. Discussion

Overcoming the implementation gap of the MUS requires improved understanding of the consequences of MUS development across social and environmental dimensions. This understanding is essential to facilitate a more integrated management approach as highlighted by previous MUS literature yet lacked the necessary structures to do so, namely, conceptual models (Abhinav et al., 2020; van den Burg et al., 2020a,b; O'Shea et al., 2022). The use of a hypothetical scenario and Delphi methodology initiated a structured decision-making approach to the seaweed aquaculture-wind farm system, aiming to enhance understanding of the consequences and enable further integrative analyses and management of commercialisation in real-life systems. The information sourced elucidates the potential consequences to social, economic, and environmental domains perceived from developing seaweed aquaculture inside an existing wind farm as a move towards MUS. The cognitive maps and impact tables illustrate the complexity of operationalising a MUS concept, highlighting various factors that should be considered in the management of developing a seaweed aquaculture-wind farm system.

4.1. Conflicting views on the impacts of MUS

An emergent theme of the assessment was the possible costs (trade-offs/risks) and benefits to different social-ecological components of the surrounding area. For example, the cognitive maps highlight that the seaweed aquaculture-wind farm system may increase and/or decrease

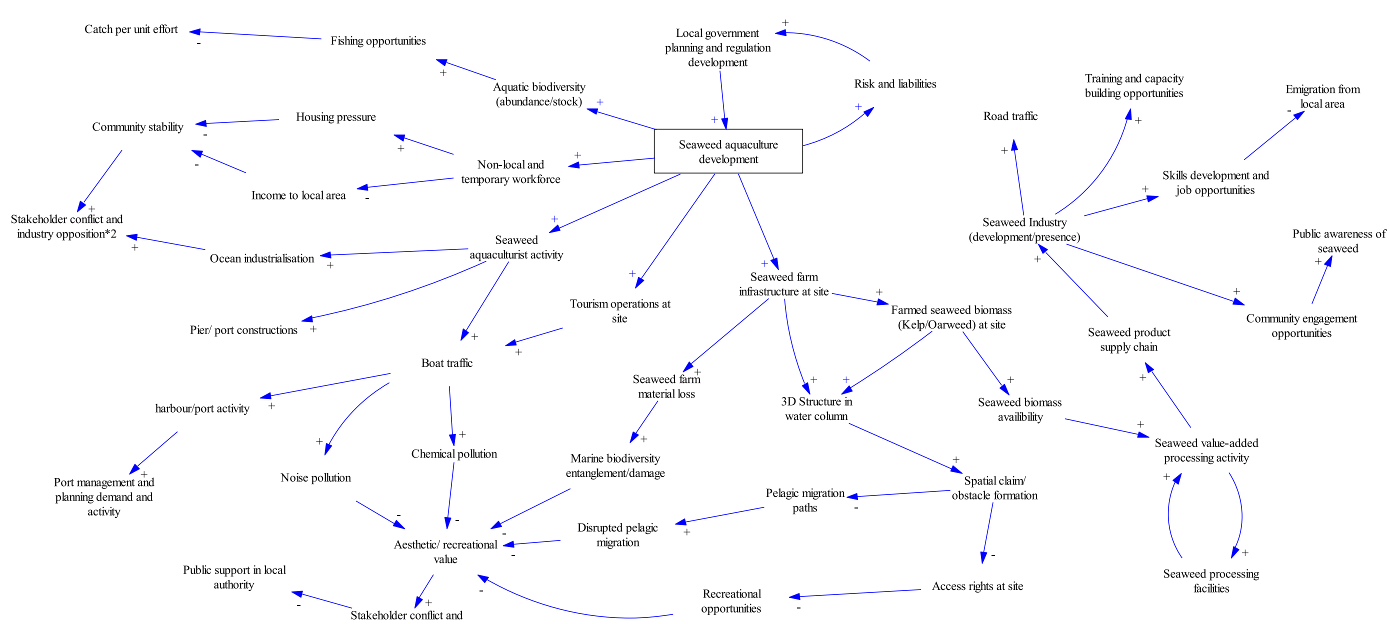

Fig. 10. Standardised and shared cognitive model on the potential impacts to the social system (social community and infrastructure) of the hypothetical scenario of expanding seaweed aquaculture inside Hornsea Wind Farm over the next ten years. -Boxed variable indicates starting node; Arrows show direction of influence between proposed variables (blue for primary and orange for additional/secondary pathways suggested by experts); Dashed lines explain key exogenous variables impacting the seaweed farm system; plus/minus symbols denote the direction of change i.e. increasing or decreasing, of child node; *n indicates secondary or tertiary impacts to/from a node. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 4
Summary of impact table describing the proposed effects resulting from integration of seaweed aquaculture and a wind farm. Table categorises the primary entity effected, the suggested impact and the SMEx of the Delphi panel that proposed the impact.

Objective	Entity	Suggested Impact	Number of identifiers
Environmental (Abiotic)	Marine Chemical Composition	Reduction in level of Chemicals at and/or around Site	13
	Marine Physical Structures	Seabed Sedimentation	5
		Seabed Damage/ Scouring	1
	Marine Hydrodynamics	Disturbance and reduction to Hydrodynamic Flow	5
	Ocean-Atmosphere	Sunlight Attenuation in Water Column	7
		Ocean Alkalisation	3
		Reduction in Climate Active Gases and Global Warming potential	5
		Increase to Climate Active Gases	4
Environmental (Biotic)	Avian Organisms	Collision potential with Wind Turbines	3
		Behavioural adaptations including feeding prevention and attraction to site	5
	Aquatic Organisms	Attraction of aquatic biodiversity to site and enhanced habitat structural complexity	9
		Damage and or increased mortality of aquatic biodiversity at site	6
		Disrupted and or reduced pelagic organisms' migration	2
		Genetic Restructuring/ Disruption in Native Seaweed Populations	1
	Ecosystem Ecology	Increased stock of Biomass in the Ecosystem	5
		Increased primary production and nutrient capture efficiency of the ecosystem	1
		Reduced Primary Production level of the Ecosystem	6
		Reduced stock of biomass in the ecosystem/disruption (unspecified) to food web dynamics/ induction of ecosystem tipping point	5
		Reduction in Eutrophication potential	4
		Non-native species introduction and biosecurity issues	4
		Reduced Seabed recovery opportunities	1
Social communities including Marine Stakeholders (non-economic) and infrastructure	Recreation	Disruption to recreational activities and reduced aesthetic value	4
		Enhancing to recreational fishing opportunities	6
	Local Social Communities	Concerns, conflicts and seaweed industry opposition with local residents	5
		Raised public awareness of seaweed	1
		Reduced emigration drive and workforce displacement from local area	2
	Public institutions/ organisations	Lowered public support for local authority	1
		Increased opportunities for training and capacity building	1
		Demand for local government planning and regulation developments	1
	Infrastructure and transportation	New port constructions and port activity including management	3
		Increased marine and road traffic	3
		New biomass processing facilities in area	5
Marine Economic Stakeholders	Wind Farm Operations	Net Gain opportunity and improved Social Licence to Operate score for OWF developer	2
		Disruption to Wind Farm logistics/ operations including increased labour and marine vessel use time	6
		Increased costs and complexity including risks and management, for OWF operations	10
		Resource sharing opportunities with bioenergy product potentials and reduced operational costs for OWF	2
		Enhanced design life of Wind Turbines	1
		Wind Farm array profitability/ efficiency of area	1
	Fisheries	Disruption with reduced income, conflict and displacement potential for fisheries including static pot and line, at the site	9
		Improved catch rate and opportunities for fisheries at and or external to the site	5
	Tourism	Increase tourism activity/potential at site	1

(continued on next page)

Table 4 (*continued*)

Objective	Entity	Suggested Impact	Number of identifiers
	Oil and Gas; Carbon Capture Storage	Limiting development potential for oil and gas, and carbon capture storage operations at the site	1
	Shipping	Reduced shipping access opportunities through site with stakeholder conflict potential	3
	Search and Rescue	disturbance to Search and Rescue operations at site	1
	Other	New marine stakeholders and entrants to marine industry	2
		Reduced Stakeholder Competition Inshore	1
Economic and Industry Development	Innovation	New research and innovation opportunities	2
		Demand for automation services	2
		Increased potential for multitrophic aquaculture at site	1
	Bio-based Industry	New Seaweed Industry Development based on the increased biomass processing activity and bio-product supply with income generation/ opportunities	13
		Opportunities for external businesses and diversification of local economy	7
		Debt creation and economic losses/ instability	5
		Workforce and knowledge demand/ development including high skilled, transferable, local and or non-local labour	7
		New Ecosystem services credit options (Cabron Dioxide, Nitrogen, Phosphate)	2
		Improvements to human and livestock health	1
		UK food independence and or increased food export	1
	Economic circularity and decarbonisation	Economic circularity capacity and activity	9
		Decarbonisation and coupled climate change mitigation	4

global warming potential depending on carbon budget of the supply chain and knock on effects to existing wind farm maintenance operations. It may promote and/or damage biodiversity as a result of providing habitat functions that supports marine life or cascading effects that threatens populations levels. It could raise income and/or cause debt depending on how the projects are implemented and prevent emigration drives in coastal areas or promote tensions in local communities. The conflicting outcomes to result from an MUS project must therefore be carefully reviewed prior to, and if progressed, during the

Table 5
Summary table of impacts that were contested by other members of the SMEx panel including their justification for disagreeing with the likelihood of impacts proposed by other SMEx and any related evidence to support their protest.

Consequence	Disagreement	Justification	Relevant Literature
Non-local or temporary work force extending from the seaweed farm leading to a decrease in income to the local area	Claim contested by an individual on the SMEx panel member	Prior to the farming activity, there wouldn't have been that income to the community anyways.	Not supplied
Reduced livestock emissions from consumption of seaweed- based products	Claim contested by an individual SMEx panel member	Some initial, and mostly lab-based, studies have suggested that halogenated, red seaweed species can reduce methane emissions from cows when incorporated into their feed. Kelps, like your model uses, are not halogenated, and to my knowledge, there is currently no indication to suggest that they would have the same effect on methane. So I suggest that you remove the "-livestock emissions" from this model.	Related evidence to counterclaim includes: Halogen chemistry of the red alga *Asparagopsis taxiformis*by McConnell and Fenical (1977) and benefits and risks of including the bromoform containing seaweed *Asparagopsis taxiformis*in feed for the reduction of methane production from ruminants by Glasson et al., (2022).
Resource sharing opportunities with bioenergy product potentials and reduced operational costs for OWF	Claim contested by an individual SMEx panel member	Bioenergy opportunity is unlikely due to economically unviable production within wind farm array; relationship between seaweed aquaculture and wind farm operator more likely to be "encouraged" through governmental incentives/policies	Related evidence to counterclaim includes: van den Burg et al. (2016); https://kennisdelen.rvo.nl/groups/view/244e11b4-4982-410f-ab62-eb94b7e23d51/community-of-practice-noordzee/blog/view/b81e1b8a-89b5-400f-98b1-1130ead4c50b/doorvaart-en-medegebruik-update-op-noordzeeloket; https://www.rvo.nl/sites/default/files/2022-11/Vragen-antwoorden-webinar-Routekaart-2030-2031.pdf
Improvements to human and livestock health	Claim contested by an individual SMEx panel member	risks to health also exist from consumption of seaweed and therefore, not always a guaranteed improvement	Related evidence to counterclaim includes: https://www.fao.org/3/cc0846en/cc0846en.pdf and Banach et al. (2020)
Economic circularity	Claim contested by an individual	More waste doesn't inherently lead to more	Not supplied

(continued on next page)

Table 5 (*continued*)

Consequence	Disagreement	Justification	Relevant Literature
capacity and activity	SMEx panel member	circularity in the economy if infrastructure or capacity for recycling isn't available in first instance	

implementation and scale up of production systems. Especially as the results of this study further extends the existing evidence base on project costs and complexity associated with the MUS (Ciravegna et al., 2024). It, therefore, cannot be assumed that the outcomes of a MUS project are solely positive or negative and may incur mixed outcomes within and across the sub-objectives of sustainability-social, economic, and environmental.

Despite the major socio-economic advantages of pursing an MUS type system being claimed by prior research-namely, minimising marine stakeholder conflicts (Abhinav et al., 2020; Przedrzymirska et al., 2021), the cognitive mapping has contradicted such claims. The integration of seaweed aquaculture was perceived by several SMEx to disrupt marine economic stakeholders, even those thought to be excluded from effects from the MUS. Stakeholders perceived to be affected included those in shipping seeking future access rights as well as ongoing fisheries that are within the wind farm array, in addition to external operations effected by knock-on effects caused by seaweed aquaculture activity (Fig. 9). With the emerging wind sector in the North Sea and heavy conflict potential expected amongst marine stakeholders (Pettersen et al., 2023), the MUS does not offer a resolution by default. Assuming otherwise could amplify conflict problems when the opposite outcome was intended from the MUS innovation.

Based on the findings of this study, the co-location of seaweed aquaculture with wind farms also carries potential to exasperate existing problems with offshore wind energy operations. Offshore wind farms have been flagged in several articles for exerting detrimental pressures onto the local environment (Rezaei et al., 2023), including disrupting fecundity and behaviour to increased mortality of marine aquatic and avian life (Galparsoro et al., 2022). The subject matter experts involved in this study perceived similar impacts, supporting the prior research (Galparsoro et al., 2022), that could result through addition of seaweed aquaculture, including raised mortality and significant disruption to ecological networks within and beyond the boundaries of Hornsea wind farm (Figs. 6 and 7).

Furthermore, the carbon sequestration potential of seaweed aquaculture as a tool to mitigate climate change is repeatedly advocated in prior research (Alleway, 2023; Duarte et al., 2022; van den Burg et al., 2023) and has been one of the promised benefits of co-locating seaweed aquaculture and wind farms (Maar et al., 2023). The cognitive maps, again, contradict these claims and highlights a more nuanced view. Instead, they demonstrate assuming climate change mitigation from seaweed aquaculture presents an incomplete picture of what may happen. The carbon budget is dependent on whole seaweed supply chain dynamics (context-dependent) and the complexity of carbon flux in social-ecological systems-increasing or decreasing through numerous direct and indirect pathways, such as disturbance of wind farm vessels (Fig. 6). Nonetheless, many of the experts foresee the positive outcomes attributed to nearshore seaweed farming such as nutrient remediation, habitat improvements and so on (Barrett et al., 2022; Hasselström et al., 2018), do still carry over into the offshore environment. Given the dichotomy of pathways evolving from the MUS project, a key question surrounds the balance between the positive outcomes vs trade-offs in pursuit of system development. To these ends, potential consequences must be considered further in a transparent, open and systematic assessment before accepting the consequences and concluding any sustainability claims in the MUS project (Gibson, 2006).

4.2. Uncertainty

It is important to note that the impacts we present (positive or negative) are not necessarily guaranteed, and the maps highlight the variability of different outcomes that may result depending on the evolution of seaweed aquaculture and event sequences extending from development. For example, seaweed biomass can be processed into a variety of high value market products as well as biofuels (for example cosmetics, Gegg and Wells, 2019), and this was reflected during the cognitive mapping process (see supplementary materials, "impact tables (standardised).exl"). Consequently, owing to the variety of product outcomes this would have implications for the extended effects that may be experienced in other social-ecological system components, such as mitigating climate active gases e.g., requiring the seaweed aquaculture to result in products with a capacity to displace fossil-based counterparts in the economy (Fig. 8). Even within the scope of this study, some experts contradicted the assertions made by others, providing evidence regarding the likelihood of a particular outcome (refer to Table 5). Given the multiple scales of seaweed aquaculture that were defined in the hypothetical case study, impact likelihood and severity are dependent on the temporal and spatial scales that were presented in the case-study and in real-life. The types of infrastructure, aquaculture practices, exact siting and timeline for development will all factor into the probabilities of the event sequences proposed within this study where the situation is under continued evolution (Buck and Buchholz; Buck et al., 2017; Bak et al., 2020). The cognitive maps and impact tables promote high-level understanding on potential outcomes of seaweed aquaculture and wind farm co-location. More importantly, though, the structured findings present the necessary entry points i.e. conceptual maps, formerly unavailable to further reduce questions of uncertainty in MUS development (O'Shea et al., 2022). Example methodologies include, but are not limited to, the use of Bayesian Network analysis, System Dynamics and other Knowledge Based Conceptual Models, that can be extrapolated from our conceptual maps and impact table (Franco and Montibeller, 2010; French, 2021; Kelly et al., 2013). The modified Delphi and cognitive mapping highlight the value of diverse perspectives when considering factors of importance in the decision to implement a seaweed aquaculture-wind farm system, with each individual panellist bringing a unique contribution of potential outcomes based on their area of expertise (even within similar fields). A theme consistent with previous application of group conceptual mapping (Cawson et al., 2020).

This study aimed to explore the potential consequences of co-locating seaweed aquaculture and wind farms, with a sub-objective to structure findings for the purpose of facilitating further IAM and developing decision support tools. The use of cognitive mapping successfully revealed the sheer range of consequences, with positive and negative implications, and presented conceptual maps that provide a vital entry point to facilitate further techniques to support sustainable management of the MUS innovation. Managers intending to implement MUS such as co-locating seaweed aquaculture and wind farms, should exercise caution and thoroughly consider all uncertainties, trade-offs, and risks that come with the project in both social and environmental domains. It's challenging, from our assessment, to conclude any definitive outcome, whether it's a specific impact's severity and likelihood or broader overarching objectives such as social-ecological sustainability. Nonetheless, the structured expert elicitation and conceptual mapping is a pivotal first step in the realisation of commercial operations of the MUS that carries significant potential across the dimensions of sustainability.

4.3. Limitations, further research and practical implications

While we have sought an approach that is comprehensive, the methodology has limitations given the resource constraints and availability of participants amongst other issues. For example, in the conceptual maps relating to the hypothetical case study presented in this research, impacts to other marine sectors such as shipping, fisheries, oil and gas, carbon capture storage, restoration and so on, were captured (Fig. 9). However, wind farms also have significant and diverging implications to tourism (Smythe et al., 2020). Despite this association, impacts to tourism-viewed in positive and/or negative light-were covered in considerably less detail compared with other sectors such as fisheries, with cognitive maps only noting increased tourism activity at the site as a direct result of adding seaweed aquaculture (Fig. 9). This outcome may be genuine with no major impact likely for tourism in our hypothetical scenario or because it was disregarded at the time of the assessment in favour of more familiar sectors such as fisheries. Our chosen method does not allow us to extract which is correct and future research must examine these details further.

Furthermore, the scenario outline aimed to provide boundaries on the cognitive mapping, however, areas were left less defined including the exact infrastructure being installed for seaweed aquaculture and siting of said infrastructure inside the wind farm array in addition to the seaweed biomass densities and characteristics of maintenance activity. Further refinement would be necessary to limit any potential effects owing to case study uncertainty; however, the qualitative nature of the study deems the effect to be minor. Further research could replicate and test further scenarios to examine how boundary conditions affected the responses and resulting cognitive mapping.

The lead author also aimed to include a diversity of perspectives in the subject matter expert panel in attempt to limit bias, however, was unable to secure representation of Asian-based experts which could influence predications. Therefore, inclusion of more non-European and North American participants in follow-up studies is strongly advised where panel diversity is crucial to improve predictions as outlined in structured elicitation protocols (Hemming et al., 2018a,b). The high-level investigation should also be counterbalanced with inclusion of local relevant parties affected by proposed development plans/projects in future research (Keen, 1997). Additionally, while government and business were represented in the sample further investigations with these particular stakeholders would be worthwhile to balance them with the higher numbers of researchers included in the sample.

The cognitive modelling process opted to keep anonymity among the subject matter experts to reduce negative group dynamics and thus did not allow for open discussion. However, discussion among SMEx can be valuable step in the cognitive modelling process and may yield alternative results, including improvements to predications (Burgman et al., 2021; Hemming et al., 2018a,b). Additional research could use further qualitative (interviews/focus group) and/or quantitative approaches to further examine the phenomena and generalise these findings more widely. Additionally, future research should also concentrate on these areas where results were contested perhaps by using a method, such as group discussion/interview, that brings those who disagree together to seek resolution and agreement (Hemming et al., 2018a,b; Cawson et al., 2020).

After proposing a visual representation of the situation, further research should continue with the structured decision-making process in the MUS. Particular efforts should be made towards evaluating the probability (likelihood and severity) of outcomes perceived by experts. Additionally, we recommend further exploration of management strategies, employing integrative assessment and modelling techniques such as Bayesian Network or Simulations (Kelly et al., 2013), which are central to the planning. As well as examining stakeholder perceptions, to assess the true sustainability potential of the MUS system in this scenario (and others) full sustainability and energy analyses (which can translate different energy, material and economic flows in solar energy joules and/or energetic flows and streams) such as Life Cycle Assessment (LCA) and Exergy analysis need to be completed (Muench and Guenther, 2013; Aghbashlo et al., 2022; Gheewala, 2023; Yousuf et al., 2022). Research shows that these types of analysis can improve efficiency, produce better designs, and improved R&D amongst other aspects. Additionally, analysis such as COMPLIMENT which integrates life cycle assessment, multi-criteria analysis and environmental performance indicators could be used to examine the industries potential (Hermann et al., 2007).

In terms of practical recommendations, it is clear that any MUS scheme will only be successful by embracing the multidimensional/multi objective and complex nature of these systems to be able to limit trade-offs across social, economic, and environmental dimensions (Bakshi, 2019; Wohlfahrt et al., 2019; Urmetzer et al., 2020). Any projects must consider the economic potential, especially of seaweed aquaculture which has been shown to be problematic (van den Burg et al., 2016) with issues having been highlighted relating to the whole seaweed processing and supply chain (Gegg and Wells, 2019) and its feasibility. Additionally, loss to other marine stakeholders needs to be considered (see Fig. 9). This type of economic data is currently lacking in the offshore MUS context (van den Burg et al., 2016).

Several projects are underway testing the feasibility of seaweed production inside wind farm arrays, where examples include H2020 UNITED (2020), MUSICA project (2020), and ULT Farms (2020). And these will be key in putting into practice the learnings developed here. These projects will facilitate a "learn-by-doing" approach that is useful in the innovation cycle for maturing activity and processes and provides information for decision-making (Hellsmark et al., 2016; IPCC, 2022). Within this, process systems engineering techniques can be used in conjunction including industrial design, experimental analysis, and techno-economic assessment to determine viable seaweed processing systems applicable to the seaweed aquaculture-wind farm case study (Bakshi, 2019; Buchner et al., 2018; Cardin, 2014) alongside energy and LCA analysis noted above. However, our research highlights that technical feasibility, while necessary for scale up, must be considered alongside other elements. Involvement of stakeholders from all areas must be ensured even in small scale pilots as the success and feasibility of the MUS system depends not just on technological feasibility but acceptance and support from a wide range of stakeholders, including the broader public. A technology push approach will not be effective in this case and wider perspectives need to be integrated (Bruton et al., nd.). Doing this in a structured manner would also allow a process evaluation to take place, an approach used across multiple disciplines, to examine how the project was delivered, the beneficiaries of the project, problems arising and how they were resolved, rather than focusing on outcomes only (Jain et al., 2004). More broadly, our study has demonstrated the value of group-based conceptual mapping for holistic evaluations of innovations in the bioeconomy transition. Previous studies were largely confined to environmental systems modelling (Cawson et al., 2020), thus our study extends the value of this method to scale-up implications of bioresource technologies.

5. Conclusion and outlook

In this study the consequences of co-locating seaweed aquaculture and existing wind farm as a move towards MUS were explored across social, economic and environmental domains. The use of a Delphi and cognitive mapping methodology generated information regarding the perceived social and environmental impacts of developing seaweed aquaculture over the next ten years inside Hornsea Wind Farm array. Impacts perceived by the group of subject matter experts tallied to 58 potential consequences and were diverse carrying positive and negative implications. In some cases, there is the potential to exacerbate existing problems attributed to wind farm development such as species fecundity and ecosystem disruption or in social terms, stakeholder conflict among marine users. On the other hand, integrating seaweed aquaculture inside a wind farm does carry significant potential to improve surrounding social and environmental conditions such as enhanced habitat structures for aquatic life and creating new economic opportunities. This dichotomous nature of outcomes and coupled uncertainty warrants further systematic investigations to support decision-making. The cognitive maps and impact tables developed in this study serve as crucial entry points for further integrative assessment and modelling techniques MUS management. These include probabilistic and simulation studies, as well as sustainability assessment tools such as exergy and lifecycle and trade-off analyses, all aimed at enhancing understanding of factors pertinent to sustainable management of MUS project(s). Given the complexity and uncertainty in addition to risk potential of co-locating seaweed and offshore wind sectors, we also recommend it is worthwhile exploring alternative development strategies to limit variability in the situation and complement ongoing offshore trials such as studies in process systems engineering. More broadly, the use of Delphi and cognitive mapping was a valuable contribution in assessing the multidimensional nature of managing innovations in the Sustainable Bioeconomy transition. Providing a means to account for multiple objectives and bring together diverse perspectives in the evaluation of conceptual stage innovations and thus, recommend the application of the methodology in other relevant settings.

Funding statement

This research has been funded by the Economic and Social Research Council as part of the London Interdisciplinary Social Science Doctoral Training Partnership, United Kingdom, undertaken by main author.

CRediT authorship contribution statement

Ryan O'Shea: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Elisa Capuzzo:** Writing – original draft, Methodology, Conceptualization. **Victoria Hemming:** Writing – original draft, Methodology, Formal analysis. **Gretchen Grebe:** Writing – original draft, Visualization, Resources, Investigation, Data curation. **Rick Stafford:** Writing – original draft, Resources, Investigation, Data curation. **Sander W.K. van den Burg:** Writing – original draft, Resources, Investigation. **Daniel Wood:** Writing – original draft, Resources, Investigation, Data curation. **Gordon Watson:** Writing – original draft, Resources, Investigation, Data curation. **Victoria Wells:** Writing – original draft, Resources, Investigation, Data curation. **Teresa Johnson:** Resources, Investigation, Data curation. **Stefan Erbs:** Resources, Investigation, Data curation. **Jaap W. van Hal:** Writing – original draft, Resources, Investigation, Data curation. **Bas Binnerts:** Writing – original draft, Resources, Investigation, Data curation. **Alexandra M Collins:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Caroline Howe:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.120696.

References

Abhinav, K.A., Collu, M., Benjamins, S., Cai, H., Hughes, A., Jiang, B., Jude, S., Leithead, W., Lin, C., Liu, H., Recalde-Camacho, L., Serpetti, N., Sun, K., Wilson, B., Yue, H., Zhou, B.Z., 2020. Offshore multi-purpose platforms for a Blue Growth: a technological, environmental and socio-economic review. Sci. Total Environ. 734, 138256 https://doi.org/10.1016/j.scitotenv.2020.138256. Elsevier B.V.

Aghbashlo, M., Hosseinzadeh-Bandbafha, H., Shahbeik, H., Tabatabaei, M., 2022. The role of sustainability assessment tools in realizing bioenergy and bioproduct systems. Biofuel Research Journal 35, 1697–1706. https://www.biofueljournal.com/article_155564.html#:~:text=10.18331/BRJ2022.9.3.5.

Aguilar, A., Twardowski, T., Wohlgemuth, R., 2019. Bioeconomy for Sustainable Development. In Biotechnology Journal 14 (Issue 8). https://doi.org/10.1002/biot.201800638. Wiley-VCH Verlag.

Alleway, H.K., 2023. Climate benefits of seaweed farming. In: Nature Sustainability. Nature Research. https://doi.org/10.1038/s41893-022-01044-x.

Anderson, J.L., Asche, F., Garlock, T., Chu, J., 2017. Aquaculture: its role in the future of food. Front. Econ. Glob. 17, 159–173. https://doi.org/10.1108/S1574-871520170000017011/FULL/XML.

Araújo, R., Vázquez Calderón, F., Sánchez López, J., Azevedo, I.C., Bruhn, A., Fluch, S., Garcia Tasende, M., Ghaderiardakani, F., Ilmjärv, T., Laurans, M., Mac Monagail, M., Mangini, S., Peteiro, C., Rebours, C., Stefansson, T., Ullmann, J., 2021. Current status of the algae production industry in Europe: an emerging sector of the blue bioeconomy. Front. Mar. Sci. 7, 626389 https://doi.org/10.3389/FMARS.2020.626389/BIBTEX.

Bak, U., Gregersen, Ó., Infante, J., 2020. Technical challenges for offshore cultivation of kelp species: lessons learned and future directions. Bot. Mar. 63 (4) https://doi.org/10.1515/bot-2019-0005, 341-353-undefined.

Bakshi, B.R., 2019. Toward Sustainable Chemical Engineering: the Role of Process Systems Engineering, vol. 10, pp. 265–288. https://doi.org/10.1146/ANNUREV-CHEMBIOENG-060718-030332, 10.1146/Annurev-Chembioeng-060718-030332.

Banach, J.L., Hoek-van den Hil, E.F., van der Fels-Klerx, H.J., 2020. Food safety hazards in the European seaweed chain. Compr. Rev. Food Sci. Food Saf. 19 (2), 332–364. https://doi.org/10.1111/1541-4337.12523. Blackwell Publishing Inc.

Banach, J.L., Hoek-van den Hil, E.F., van der Fels-Klerx, H.J., 2022. Floating Offshore Wind Turbines: Current Status and Future Prospects. Energies 16 (1), 2. https://doi.org/10.3390/EN16010002, 2023, 16, 2.

Barrett, L.T., Theuerkauf, S.J., Rose, J.M., Alleway, H.K., Bricker, S.B., Parker, M., Petrolia, D.R., Jones, R.C., 2022. Sustainable growth of non-fed aquaculture can generate valuable ecosystem benefits. Ecosyst. Serv. 53, 101396 https://doi.org/10.1016/J.ECOSER.2021.101396.

Bates, A., Firestone, J., 2015. A comparative assessment of proposed offshore wind power demonstration projects in the United States. Energy Res. & Social Sci. 10, 192–205. https://doi.org/10.1016/J.ERSS.2015.07.007.

Beaudrie, C.E.H., Kandlikar, M., Ramachandran, G., 2011. Using expert judgment for risk assessment. Assessing Nanoparticle Risks to Human Health 109–138. https://doi.org/10.1016/B978-1-4377-7863-2.00005-4.

Brady, S.R., 2015. Utilizing and adapting the Delphi method for use in qualitative research. Int. J. Qual. Methods 14 (5), 160940691562138. https://doi.org/10.1177/1609406915621381.

Bruton, T, Lyons, H., Lerat, Y, Stanley, M., Rasmussen, M.., n.d.. A review of the potential of Marine Algae as a Source of Biofuel in Ireland. Sustainable Energy Ireland 1, 72–73. https://www.researchgate.net/publication/309185965.

Buchner, G.A., Zimmermann, A.W., Hohgräve, A.E., Schomäcker, R., 2018. Techno-economic assessment framework for the chemical industry - based on technology readiness levels. Ind. Eng. Chem. Res. 57 (25), 8502–8517. https://doi.org/10.1021/acs.iecr.8b01248.

Buck, B.H., Buchholz, C.M., 2004. The offshore-ring: a new system design for the open ocean aquaculture of macroalgae. J. Appl. Phycol. 16 (5), 355–368. https://doi.org/10.1023/B:JAPH.0000047947.96231.EA/METRICS.

Buck, B.H., Nevejan, N., Wille, M., Chambers, M.D., Chopin, T., 2017. Offshore and multi-use aquaculture with extractive species: seaweeds and bivalves. In: Aquaculture Perspective of Multi-Use Sites in the Open Ocean: the Untapped Potential for Marine Resources in the Anthropocene. Springer International Publishing, pp. 23–69. https://doi.org/10.1007/978-3-319-51159-7_2.

Buck, B.H., Troell, M.F., Krause, G., Angel, D.L., Grote, B., Chopin, T., 2018. State of the art and challenges for offshore Integrated multi-trophic aquaculture (IMTA). Front. Mar. Sci. 5 (MAY), 165. https://doi.org/10.3389/fmars.2018.00165.

Burgman, M., Layman, H., French, S., 2021. Eliciting model structures for multivariate probabilistic risk analysis. Frontiers in Applied Mathematics and Statistics 0, 36. https://doi.org/10.3389/FAMS.2021.668037.

Buschmann, A.H., Camus, C., Infante, J., Neori, A., Israel, Á., Hernández-González, M.C., Pereda, S.V., Gomez-Pinchetti, J.L., Golberg, A., Tadmor-Shalev, N., Critchley, A.T., 2017. Seaweed production: overview of the global state of exploitation, farming and emerging research activity. Eur. J. Phycol. 52 (4), 391–406. https://doi.org/10.1080/09670262.2017.1365175.

Cardin, M.A., 2014. Enabling flexibility in engineering systems: a taxonomy of procedures and a design framework. Journal of Mechanical Design, Transactions of the ASME 136 (1). https://doi.org/10.1115/1.4025704/375859.

Cawson, J.G., Hemming, V., Ackland, A., Anderson, W., Bowman, D., Bradstock, R., Brown, T.P., Burton, J., Cary, G.J., Duff, T.J., Filkov, A., Furlaud, J.M., Gazzard, T., Kilinc, M., Nyman, P., Peacock, R., Ryan, M., Sharples, J., Sheridan, G., et al., 2020. Exploring the key drivers of forest flammability in wet eucalypt forests using expert-derived conceptual models. Landsc. Ecol. 35 (8), 1775–1798. https://doi.org/10.1007/S10980-020-01055-Z/TABLES/5.

Chirosca, A.M., Rusu, L., Bleoju, A., 2022. Study on wind farms in the North Sea area. Energy Rep. 8, 162–168. https://doi.org/10.1016/J.EGYR.2022.10.244.

Ciravegna, E., van Hoof, L., Frier, C., Maes, F., Rasmussen, H.B., Soete, A., van den Burg, S.W.K., 2024. The hidden costs of multi-use at sea. Mar. Pol. 161, 106017 https://doi.org/10.1016/J.MARPOL.2024.106017.

Dalkey, N., Helmer, O., 1963. An experimental application of the Delphi method to the use of experts method to the use of experts *t. Source: Manag. Sci. 9 (3), 458–467.

Dincer, I., Cozzani, V., Crivellari, A., 2021. Offshore renewable energy options. Hybrid Energy Systems for Offshore Applications 7–18. https://doi.org/10.1016/B978-0-323-89823-2.00002-6.

Duarte, C.M., Bruhn, A., Krause-Jensen, D., 2022. A seaweed aquaculture imperative to meet global sustainability targets. Nat. Sustain. 5 (3), 185–193. https://doi.org/10.1038/s41893-021-00773-9. Nature Research.

Eden, C., 2004. Analyzing cognitive maps to help structure issues or problems. Eur. J. Oper. Res. 159 (3), 673–686. https://doi.org/10.1016/S0377-2217(03)00431-4.

European Commission, 2021. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS -Strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021 to 2030. https://eur-lex.europa.eu/resource.html?uri=cellar:bab1f9a7-b30b-11eb-8aca-01aa75ed71a1.0022.02/DOC_1&format=PDF.

European Commission, 2022. Communication from the Commission to the European Parliament, The European Council, the Council, the European Economic and Social Committee and the Committee of the Regions-. Repowereu Plan 1, 1–20. https://eur-lex.europa.eu/resource.html?uri=cellar:fc930f14-d7ae-11ec-a95f-01aa75ed71a1.0001.02/DOC_1&format=PDF.

Franco, L.A., Montibeller, G., 2010. Facilitated modelling in operational research. Eur. J. Oper. Res. 205 (3), 489–500. https://doi.org/10.1016/j.ejor.2009.09.030.

French, S., 2021. From soft to hard elicitation. J. Oper. Res. Soc. https://doi.org/10.1080/01605682.2021.1907244.

Froehlich, H.E., Smith, A., Gentry, R.R., Halpern, B.S., 2017. Offshore aquaculture: I know it when I see it. Front. Mar. Sci. 4 (MAY), 154. https://doi.org/10.3389/FMARS.2017.00154/BIBTEX.

Galparsoro, I., Menchaca, I., Garmendia, J.M., Borja, Á., Maldonado, A.D., Iglesias, G., Bald, J., 2022. Reviewing the ecological impacts of offshore wind farms, 2022 Npj Ocean Sustainability 1 (1), 1–8. https://doi.org/10.1038/s44183-022-00003-5, 1, 1.

García-Poza, S., Leandro, A., Cotas, C., Cotas, J., Marques, J.C., Pereira, L., Gonçalves, A. M.M., 2020. The evolution road of seaweed aquaculture: cultivation technologies and the industry 4.0. In: International Journal of Environmental Research and Public Health, vol. 17. MDPI AG, pp. 1–42. https://doi.org/10.3390/ijerph17186528, 18.

Garlock, T., Asche, F., Anderson, J., Ceballos-Concha, A., Love, D.C., Osmundsen, T.C., Pincinato, R.B.M., 2022. Aquaculture: the missing contributor in the food security agenda. Global Food Secur. 32, 100620 https://doi.org/10.1016/J.GFS.2022.100620.

Gegg, P., Wells, V.K., 2019. The development of seaweed-derived fuels in the UK: an analysis of stakeholder issues and public perceptions. Energy Pol. 133, 110924 https://doi.org/10.1016/j.enpol.2019.110924.

Gheewala, S.H., 2023. Life cycle assessment for sustainability assessment of biofuels and bioproducts. Biofuel Research Journal 10 (1), 1810–1815. https://doi.org/10.18331/BRJ2023.10.1.5.

Gibson, R.B., 2006. Impact Assessment and Project Appraisal Sustainability assessment: basic components of a practical approach. Impact Assess. Proj. Apprais. 24 (3), 170–182. https://doi.org/10.3152/147154606781765147.

Glasson, C.R.K., Kinley, R.D., de Nys, R., King, N., Adams, S.L., Packer, M.A., Svenson, J., Eason, C.T., Magnusson, M., 2022. Benefits and risks of including the bromoform containing seaweed Asparagopsis in feed for the reduction of methane production from ruminants. Algal Research 64, 102673. https://doi.org/10.1016/J.ALGAL.2022.102673.

H2020 UNITED, 2020. UNITED project. https://www.h2020united.eu/.

Hasselström, L., Visch, W., Gröndahl, F., Nylund, G.M., Pavia, H., 2018. The impact of seaweed cultivation on ecosystem services - a case study from the west coast of Sweden. Mar. Pollut. Bull. 133, 53–64. https://doi.org/10.1016/j.marpolbul.2018.05.005.

Hellsmark, H., Frishammar, J., Söderholm, P., Ylinenpää, H., 2016. The role of pilot and demonstration plants in technology development and innovation policy. Res. Pol. 45 (9), 1743–1761. https://doi.org/10.1016/J.RESPOL.2016.05.005.

Hemming, V., Burgman, M.A., Hanea, A.M., McBride, M.F., Wintle, B.C., 2018a. A practical guide to structured expert elicitation using the IDEA protocol. Methods Ecol. Evol. 9 (1), 169–180. https://doi.org/10.1111/2041-210X.12857.

Hemming, V., Walshe, T.V., Hanea, A.M., Fidler, F., Burgman, M.A., 2018b. Eliciting improved quantitative judgements using the IDEA protocol: a case study in natural resource management. PLoS One 13 (6), e0198468. https://doi.org/10.1371/JOURNAL.PONE.0198468.

Hemming, V., Camaclang, A.E., Adams, M.S., Burgman, M., Carbeck, K., Carwardine, J., Chadès, I., Chalifour, L., Converse, S.J., Davidson, L.N.K., Garrard, G.E., Finn, R., Fleri, J.R., Huard, J., Mayfield, H.J., Madden, E.M.D., Naujokaitis-Lewis, I., Possingham, H.P., Rumpff, L., et al., 2022. An introduction to decision science for conservation. Conserv. Biol. 36 (1), e13868 https://doi.org/10.1111/COBI.13868.

Hermann, B.G., Kroeze, C., Jawjit, W., 2007. Assessing environmental performance by combining life cycle assessment, multi-criteria analysis and environmental performance indicators. J. Clean. Prod. 15 (18), 1787–1796. https://doi.org/10.1016/j.jclepro.2006.04.004.

Hochman, G., Palatnik, R.R., 2022. The Economics of Aquatic Plants: The Case of Algae and Duckweed 14, 555–577. https://doi.org/10.1146/ANNUREV-RESOURCE-111920-011624, 10.1146/Annurev-Resource-111920-011624.

Hodgson, E.E., Essington, T.E., Samhouri, J.F., Allison, E.H., Bennett, N.J., Bostrom, A., Cullen, A.C., Kasperski, S., Levin, P.S., Poe, M.R., 2019. Integrated risk assessment for the blue economy. Front. Mar. Sci. 6 (SEP), 609. https://doi.org/10.3389/fmars.2019.00609.

Holmer M, 2010. Environmental issues of fish farming in offshore waters: perspectives, concerns and research needs. Aquaculture Environment Interactions 1, 57–70. https://www.int-res.com/articles/aei2010/1/q001p057.pdf.

International Energy Agency, 2022. Renewables 2022. www.iea.org.

IPCC, 2022. Mitigation of Climate Change Climate Change 2022 Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change 1, 181–189.

Jain, R., Martyniuk, A.O., Harris, M.M., Niemann, R.E., Woldmann, K., 2004. Evaluating the commercial potential of emerging technologies. Int. J. Technol. Transf. Commer. 2 (1), 32–50. https://doi.org/10.1504/IJTTC.2003.001800.

Keen, M., 1997. Catalysts for Change: the Emerging Role of Participatory Research in Land Management.

Kelly, R.A., Jakeman, A.J., Barreteau, O., Borsuk, M.E., ElSawah, S., Hamilton, S.H., Henriksen, H.J., Kuikka, S., Maier, H.R., Rizzoli, A.E., van Delden, H., Voinov, A.A., 2013. Selecting among five common modelling approaches for integrated environmental assessment and management. Environ. Model. Software 47, 159–181. https://doi.org/10.1016/j.envsoft.2013.05.005.

Luna-Reyes, L.F., Andersen, D.L., 2003. Collecting and analyzing qualitative data for system dynamics: methods and models. Syst. Dynam. Rev. 19 (4), 271–296. https://doi.org/10.1002/SDR.280.

Maar, M., Holbach, A., Boderskov, T., Thomsen, M., Buck, B.H., Kotta, J., Bruhn, A., 2023. Multi-use of offshore wind farms with low-trophic aquaculture can help achieve global sustainability goals. Communications Earth & Environment 2023 4 (1), 1–14. https://doi.org/10.1038/s43247-023-01116-6, 1, 4.

Marine Management Organisation, 2019. Identification of areas of aquaculture potential in English waters (MMO 1184). www.nationalarchives.gov.uk/doc/open-government.

Martin, T.G., Burgman, M.A., Fidler, F., Kuhnert, P.M., Low-Choy, S., Mcbride, M., Mengersen, K., 2012. Eliciting expert knowledge in conservation science. Conserv. Biol. 26 (1), 29–38. https://doi.org/10.1111/J.1523-1739.2011.01806.X.

McConnell, O., Fenical, W., 1977. Halogen chemistry of the red alga Asparagopsis. Phytochemistry 16 (3), 367–374. https://doi.org/10.1016/0031-9422(77)80067-8.

Muench, S., Guenther, E., 2013. A systematic review of bioenergy life cycle assessments. Appl. Energy 112, 257–273. https://doi.org/10.1016/j.apenergy.2013.06.001.

Mukherjee, N., Hugé, J., Sutherland, W.J., Mcneill, J., Van Opstal, M., Dahdouh-Guebas, F., Koedam, N., 2015. The Delphi technique in ecology and biological conservation: applications and guidelines. Methods Ecol. Evol. 6 (9), 1097–1109. https://doi.org/10.1111/2041-210X.12387.

MUSICA, 2020. Musica Project – MULTIPLE USE OF SPACE FOR ISLAND CLEAN AUTONOMY. https://musica-project.eu/.

Okoli, C., Pawlowski, S.D., 2004. The Delphi method as a research tool: an example, design considerations and applications. Inf. Manag. 42 (1), 15–29. https://doi.org/10.1016/j.im.2003.11.002.

Ørsted, 2020. Hornsea project one- about the project. https://hornseaprojectone.co.uk/about-the-project#project-timeline-2020.

O'Shea, R., Collins, A., Howe, C., 2022. Offshore Multi-use setting: introducing integrative assessment modelling to alleviate uncertainty of developing Seaweed Aquaculture inside Wind Farms. Environmental Challenges 8, 100559. https://doi.org/10.1016/J.ENVC.2022.100559.

Page, S., 2008. The Difference: How the Power of Diversity Creates Better Groups, Firms, Schools, and Societies. Princeton University Press. https://eric.ed.gov/?id=ED539561.

Pettersen, S., Aarnes, S., Arnesen, B., Pretlove, B., Ervik, A.K., Rusten, M., 2023. Offshore wind in the race for ocean space: a forecast to 2050. J. Phys. Conf. 2507 (1), 012005 https://doi.org/10.1088/1742-6596/2507/1/012005.

Pınarbaşı, K., Galparsoro, I., Borja, Á., Stelzenmüller, V., Ehler, C.N., Gimpel, A., 2017. Decision support tools in marine spatial planning: present applications, gaps and future perspectives. Mar. Pol. 83, 83–91. https://doi.org/10.1016/J.MARPOL.2017.05.031.

Przedrzymirska, J., Zaucha, J., Calado, H., Lukic, I., Bocci, M., Ramieri, E., Varona, M.C., Barbanti, A., Depellegrin, D., De Sousa Vergílio, M., Schultz-Zehden, A., Onyango, V., Papaioannou, E., Buck, B.H., Krause, G., Felix Schupp, M., Läkamp, R., Szefler, K., Michałek, M., et al., 2021. Multi-use of the sea as a sustainable development instrument in five EU sea basins. Sustainability 2021 13 (15), 8159. https://doi.org/10.3390/SU13158159, 8159, 13.

Rezaei, F., Contestabile, P., Vicinanza, D., Azzellino, A., 2023. Towards understanding environmental and cumulative impacts of floating wind farms: lessons learned from the fixed-bottom offshore wind farms. Ocean Coast Manag. 243, 106772 https://doi.org/10.1016/J.OCECOAMAN.2023.106772.

Roleda, M.Y., Hurd, C.L., 2019. Seaweed nutrient physiology: application of concepts to aquaculture and bioremediation 58 (5), 552–562. https://doi.org/10.1080/00318884.2019.1622920, 10.1080/00318884.2019.1622920.

Smythe, T., Bidwell, D., Moore, A., Smith, H., McCann, J., 2020. Beyond the beach: tradeoffs in tourism and recreation at the first offshore wind farm in the United States. Energy Res. Social Sci. 70, 101726 https://doi.org/10.1016/J.ERSS.2020.101726.

Steins, N.A., Veraart, J.A., Klostermann, J.E.M., Poelman, M., 2021. Combining offshore wind farms, nature conservation and seafood: lessons from a Dutch community of practice. Mar. Pol. 126, 104371 https://doi.org/10.1016/J.MARPOL.2020.104371.

Susskind, L., Chun, J., Gant, A., Hodgkins, C., Cohen, J., Lohmar, S., 2022. Sources of opposition to renewable energy projects in the United States. Energy Policy 165, 112922. https://doi.org/10.1016/J.ENPOL.2022.112922.

Sutherland, W.J., Woodroof, H.J., 2009. The need for environmental horizon scanning. Trends Ecol. Evol. 24 (10), 523–527. https://doi.org/10.1016/J.TREE.2009.04.008.
TGS 4Coffshore, 2024. Global offshore renewable map | 4C offshore. Retrieved. https://map.4coffshore.com/offshorewind/.
Torres, M.D., Kraan, S., Domínguez, H., 2019. Seaweed biorefinery. In: Reviews in Environmental Science and Biotechnology, vol. 18. Springer, Netherlands, pp. 335–388. https://doi.org/10.1007/s11157-019-09496-y, 2.
Troell, M., Joyce, A., Chopin, T., Neori, A., Buschmann, A.H., Fang, J.G., 2009. Ecological engineering in aquaculture — potential for integrated multi-trophic aquaculture (IMTA) in marine offshore systems. Aquaculture 297 (1–4), 1–9. https://doi.org/10.1016/J.AQUACULTURE.2009.09.010.
ULTFarms, 2020. Home | ULTFARMS. https://ultfarms.eu/.
United Nations, 2015. Sustainable Development Goals .:. Sustainable Development Knowledge Platform. https://sustainabledevelopment.un.org/?menu=1300.
Urmetzer, S., Lask, J., Vargas-Carpintero, R., Pyka, A., 2020. Learning to change: transformative knowledge for building a sustainable bioeconomy. Ecol. Econ. 167 https://doi.org/10.1016/j.ecolecon.2019.106435.
van den Burg, S.W.K., van Duijn, A.P., Bartelings, H., van Krimpen, M.M., Poelman, M., 2016. The economic feasibility of seaweed production in the North Sea. Aquacult. Econ. Manag. 20 (3), 235–252. https://doi.org/10.1080/13657305.2016.1177859.
van den Burg, S.W.K., Röckmann, C., Banach, J.L., van Hoof, L., 2020a. Governing risks of multi-use: seaweed aquaculture at offshore wind farms. Front. Mar. Sci. 7 https://doi.org/10.3389/fmars.2020.00060.
van den Burg, S.W.K., Schupp, M.F., Depellegrin, D., Barbanti, A., Kerr, S., 2020b. Development of multi-use platforms at sea: barriers to realising Blue Growth. Ocean Eng. 217, 107983 https://doi.org/10.1016/J.OCEANENG.2020.107983.
van den Burg, S.W.K., Termeer, E.E.W., Skirtun, M., Poelman, M., Veraart, J.A., Selnes, T., 2022. Exploring mechanisms to pay for ecosystem services provided by mussels, oysters and seaweeds. Ecosyst. Serv. 54, 101407 https://doi.org/10.1016/J.ECOSER.2022.101407.
van den Burg, S.W.K., Koch, S.J.I., Poelman, M., Veraart, J., Selnes, T., Foekema, E.M., Lansbergen, R., 2023. Seaweed as climate mitigation solution: categorizing and reflecting on four climate mitigation pathways. Wiley Interdisciplinary Reviews: Clim. Change e868. https://doi.org/10.1002/WCC.868.
Gregory, R, Failing, L, Harstone, M, Long, G, McDaniels, T, Ohlson, D., 2012. Structured Decision Making: A Practical Guide to Environmental Management Choices | Wiley, vol. 1. Wiley. https://www.wiley.com/en-gb/Structured+Decision+Making:+A+Practical+Guide+to+Environmental+Management+Choices-p-9781444333411.
Vensim. (n.d.). Retrieved December 20, 2022, from https://vensim.com/..
Vercammen, A., Burgman, M., 2019. Untapped potential of collective intelligence in conservation and environmental decision making. Conserv. Biol. 33 (6), 1247–1255. https://doi.org/10.1111/COBI.13335.
Vermeulen-Miltz, E., Clifford-Holmes, J.K., Scharler, U.M., Lombard, A.T., 2023. A system dynamics model to support marine spatial planning in Algoa Bay, South Africa. Environ. Model. Software 160. https://doi.org/10.1016/j.envsoft.2022.105601.
Wohlfahrt, J., Ferchaud, F., Gabrielle, B., Godard, C., Kurek, B., Loyce, C., Therond, O., 2019. Characteristics of bioeconomy systems and sustainability issues at the territorial scale. A review. J. Clean. Prod. 232, 898–909. https://doi.org/10.1016/j.jclepro.2019.05.385. Elsevier Ltd.
Yousuf, M.U., Abbasi, M.A., Kashif, M., Umair, M., 2022. Energy, exergy, economic, environmental, energoeconomic, exergoeconomic, and enviroeconomic (7E) analyses of wind farms: a case study of Pakistan. Environ. Sci. Pollut. Control Ser. 29 (44), 67301–67324. https://doi.org/10.1007/S11356-022-20576-5/TABLES/6.