Offshore Multi-use setting: Introducing integrative assessment modelling to alleviate uncertainty of developing Seaweed Aquaculture inside Wind Farms

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A R T I C L E   I N F O

Keywords:
Offshore multi-use setting
Seaweed aquaculture
Sustainability
Bioeconomy
Integrative assessment

A B S T R A C T

The offshore multi-use setting is a concept that reduces spatial competition in the marine economy. Seaweed Aquaculture inside Wind Farms has been suggested as a multi-use setting design, however, the uncertainty surrounding impacts associated with multi-use setting activities is a key barrier to the development of the concept. To begin alleviating uncertainty on the Seaweed Aquaculture-Wind Farm system, a systematic literature review was performed to identify the potential negative consequences of developing seaweed aquaculture inside of Wind Farms. Findings suggest negative consequences may result across multiple objectives. The study findings were used to construct cognitive models that are necessary to facilitate further integrative assessment modelling on social and ecological impacts of integrating seaweed aquaculture and Wind Farms. The interdisciplinary frameworks and research strategy proposed by this study is the first attempt to formalise holistic sustainability assessment and novel management of an emerging bioeconomic innovation being pursued in Europe.

1. Introduction

The “Blue Economy”, the sustainable use of marine resources for economic growth is predicted to grow at double the rate of the mainstream economy by 2030 (Commission European, 2021a) and consequently will increase competition for marine resources in the coming decades (Hodgson et al., 2019; European Commission, 2021b). A key question will therefore be around how to increase efficiency as well as resource and space-sharing amongst multiple users. Offshore multi-use setting (MUS) is a concept that has been developed to promote the efficient use of ocean space amongst stakeholders by co-locating industrial activities (Abhinav et al., 2020). Seaweed Aquaculture (SA), located inside Wind Farms, has been proposed as a potential MUS (Buck et al., 2018). As they are fixed-structures, Wind Farms can result in the exclusion of other marine stakeholders, such as large fisheries and shipping. Consequently, by including seaweed aquaculture within these zones, it is possible to utilise space that would otherwise not be used by other marine stakeholders, thus reducing spatial competition for marine resources (Abhinav et al., 2020). Unfortunately, there is limited integrated understanding of impacts associated with multi-use setting activities which limits designs for such systems and is a major barrier to the further development of the concept of MUS (van den Burg et al., 2020b).

Seaweed aquaculture is the cultivation of seaweed species, an aquatic photosynthetic organism also known as macroalgae (García-Poza et al., 2020). Seaweed biomass can be considered to be a renewable resource, as macroalgae contain a range of compounds that meet food/feed, cosmetic, pharmacy, fertiliser and energy purposes (Balina et al., 2017). One form of seaweed processing is being developed known as bio-refining whereby compounds are extracted in stages and remaining biomass is used for biofuel and fertiliser production (Balina et al., 2017; Sadhukhan et al., 2019). A Life-Cycle Assessment (LCA) of the process demonstrates that bio-refinement may potentially offer a decarbonisation pathway for economies otherwise dependent on fossil fuels and techno-economic assessments (TEA) of the bio-refineries process demonstrate cost-effective production is feasible under certain conditions (Segheta et al., 2016; Sadhukhan et al., 2019). Furthermore, expanding SA may deliver additional benefits to communities including enhancing ecosystem services such as providing habitats for marine life, nutrient regulation, carbon regulation, reducing ocean acidification and impacts from climate change (Hasselström et al., 2018).

The development of an industry based on Seaweed would potentially support the broader industrial concept known as the Sustainable and/or Circular Bioeconomy (SCB). This is especially true in the context of Europe which has dedicated industrial plans for an SCB and an emerging aquaculture sector (Fritsche et al., 2020; Araújo et al., 2021; von Braun, 2018). The SCB, otherwise known as the “Bioeconomy”, broadly represents an amalgamation of biotechnological and scientific knowledge within the political objective of using existing and new bi-

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https://doi.org/10.1016/j.envc.2022.100559
Received 18 March 2022; Received in revised form 19 May 2022; Accepted 23 May 2022
2667-0100/© 2022 Published by Elsevier B.V.
ological resources in a “sustainable and economic way” (Aguilar et al., 2019). The normative position of the Bioeconomy is the Sustainable Development Goals (SDGs) and thus infers that activities within it are managed in order to contribute to the objective of balancing environmental, societal, and economic goals that have been outlined by the SDG framework (Fig. 1) (Aguilar et al., 2019; European Union, 2018; Gawel et al., 2019).

Although seaweed aquaculture offers many potential benefits, concerns about the environmental and social impacts of co-locating SA inside Wind Farms have been raised (van den Burg et al., 2020a). These include decreasing the primary production of existing habitats, reduction of biodiversity and impacts on human health resulting from the accidental ingestion of anti-biofouling pollutants absorbed by seaweed. However, the concerns about SA within a multi-use setting, and the MUS concept more generally, are mostly speculative and the impacts are uncertain (van den Burg et al., 2020a, 2020b). This is due to limited empirical evidence from pilot studies and knowledge on the topic alongside the complexity of the impacts (van den Burg et al., 2020b, 2020b). Nonetheless, the perception of environmental and social problems, whether likely or not, will hinder the development of the concept of seaweed aquaculture within a MUS (van den Burg et al., 2020b) thus preventing the further development of a potentially important de-carbonisation mechanism and efficient use of marine resource space. It is therefore critical that the uncertainty surrounding social and ecological impacts caused by the seaweed aquaculture-wind farm system is alleviated to advance the bioeconomic innovation that has been proposed and provide a holistic sustainable management procedure that is currently lacking. To this end, an integrative assessment and modelling approach covering social, economic and environmental objectives is required.

Integrative Assessment and Modelling (IAM) is a structured evaluation approach, used in systems science and natural resource management, to elucidate the interconnections between social and natural dimensions (Sayer et al., 2001; Hamilton et al., 2015; IPCC, 2014), and is a potentially useful tool for improving the understanding of SA impacts within a multi-use setting (van den Burg et al., 2020a). Integrated frameworks are developed and used in computational simulations to explain and predict system behaviours across time and space (Ewert et al., 2013). The information produced can assist the decision-making process in cases where empirical data is not available (Kelly et al., 2013). IAM may also be useful is assessing the positive and negative impact of innovations within the bioeconomy across the three dimensions of sustainability: economic, societal, and environmental (Schutter et al., 2019; Wohlfahrt et al., 2019). Thus, IAM will provide useful information that is necessary to support the continued development of MUS, including the use of seaweed aquaculture in coupled wind farm settings.

Operationalising the IAM approach to understand the social-ecological interactions of SA expansion inside Wind Farms and to address uncertainty in decision-making can be done using two main modelling methods: namely, Bayesian Networks (BN) and Knowledge-Based Models (KBM) (Kelly et al., 2013). However, to the best of authors’ knowledge, no existing frameworks have been built for concurrently evaluating the impacts to the social, economic, and environmental dimensions of the system from deployment of seaweed aquaculture within Wind Farms. As a precursor to operationalise IAM for seaweed aquaculture within Wind Farms, the aim of this project was to propose a series of conceptual models, defined henceforth as causal diagrams, on the potential negative consequences of deploying SA inside a Wind Farm. To do this, a systematic review of the literature, adapted from the Rapid Evidence Assessment protocol (Collins et al., 2015), was used to identify and collate evidence on the observed and perceived impacts of seaweed aquaculture on the social, economic and environmental dimensions of the system. This resulting information was used to identify potential negative consequences and to define the relationships as a causal diagram, between SA-Wind-Farm system and surrounding landscape. The causal diagrams are the first attempt at creating the needed entry point for further IAM research including probabilistic and simulation, on the SA-Wind-Farm system. Moreover, the causal diagrams provide an initial management tool for understanding the range of potential consequences practitioners will need to navigate in promoting SA within multi-use systems.

In this paper we first provide the methodology used to systematically collate information on potential impacts, then present the results of the searches organised into causal diagrams and finally discuss the application of the results for further work in understanding of the impacts of SA-Wind-Farm scenario, limitations and the broader implications of this evaluation technique for sustainable management of innovations in the Bioeconomy.

2. Methodology

A systematic review of the literature is an approach used to search and collate available evidence on a selected topic and research question (James et al., 2016). The systematic review for this study was constructed around the topic of “potential adverse consequences to environ-
mental and social dimensions caused by development of seaweed aquaculture inside Wind Farms”. The evidence collection and synthesis broadly followed the guidelines for “rapid evidence assessment” outlined in (Collins et al., 2015). The United Kingdom (UK) is the case study region for the research project and therefore, the review focused on evidence that was applicable to the UK. As the available evidence from UK-based studies is limited, the scope of the search expanded to capture studies based in North-West Europe, including: United Kingdom, Norway, Sweden, Denmark, Netherlands, Belgium, France, Germany and Republic of Ireland. The justification to include these countries was based on the fact that they form part of two Large Marine Ecosystems (LMEs) with the UK: the Celtic-Biscay Shelf and the North Sea (Aquarone and Adams, 2020; Aquarone et al., 2020). LMEs are coastal and ocean areas with ecologically definable characteristics and boundaries (Belkin et al., 2009) which allowed the authors to bound the study to ensure that only relevant information was captured. For example, impact analyses of tropical climate were not included but extrapolation to the UK context could occur due to the assumed similar ecosystem characteristics found within LME boundaries. Although, marine Wind Farm sites are typically further offshore, there is minimal evidence on the impacts of offshore seaweed aquaculture and therefore, the scope combined both nearshore and offshore seaweed aquaculture articles in order to provide a broader evidence-base.

The review was a multistage process. The search strategy was performed between August to September 2020 and the review was completed by February 2021. A workflow diagram detailing the stages of the review are summarised in Fig. 2. The full library can be found in supplementary materials.

2.1. Search strategy

To perform the systematic review, the following platforms were explored:

- Scopus
- Web of Science Core Collection
- EBSCO

These were chosen to broaden the evidence search with each platform having differing journal access. Additionally, attempting to limit potential bias of using a single platform that may have resulted in excluding relevant evidence not contained within the platforms scope. Prior to conducting the main search of the literature databases, a pilot search was performed using Scopus to determine the final search string. The pilot study involved adding additional terms until reaching a saturation point whereby additional terms resulted in minimal change to the total results discovered. A search string was created using terms relating to the primary question:

What are the adverse impacts of seaweed aquaculture to social and environmental systems as described in North-West European studies?

To ensure a comprehensive search of the databases, variations of the terms were combined using Boolean search operators, including different forms of spelling, impacts and areas of interest. The search string was reviewed at different stages to ensure that the articles found were, in fact, relevant to the study question. The final search string consisted of 3 themes: seaweed aquaculture, impact analysis and location specification. For a full breakdown of the search string including modifications

Fig. 2. Workflow detailing the different stages of the systematic review of the literature on potential adverse consequences to environmental and social dimensions caused by development of seaweed aquaculture inside Wind Farms.
made, see Table 5 and Table 6 in the supplementary materials. An initial search was performed using the location string one in Table 5. A follow up search was made in Web of Science to extend the countries list based on North-West European nations.

Additionally, a search of the grey literature search was performed on the 15/09/2020, this used a modified search string used in Google to collect grey literature. Due to the character limit in the google search bar, names of known relevant institutions were combined with the terms “seaweed aquaculture” AND “risk” OR “impact” AND .PDF to identify grey literature of relevance. The institutions included were Centre for Environment, Fisheries and Aquaculture Science (CEFAS), Marine Management Organisation (MMO), The Scottish Association for Marine Science (SAMS), European Union (EU) Website, Food and Agriculture Organisation (FAO) and United Nations Global compact. A snowballing technique was also applied for articles identified within the captured evidence that were discussed and introduced effects previously not captured in the main search. The combination of multiple databases and processes used to search databases were believed to capture all relevant materials for answering the research question and reduce any potential bias.

2.2. Study eligibility criteria and screening

The results from the scientific and grey literature searches were imported into Endnote version X9.1 and duplicates were removed. Inclusion/ exclusion criteria were developed based on the primary question before the screening commenced. The criteria were created to structure the review of articles within the boundary of the primary question. Articles were included in the final review if they met the Population, Intervention, Comparator and Outcome (PICO) criteria summarised in Table 1. A screening protocol was built based on the PICO table to guide the review in identifying the studies of relevance to answer the primary question.

Screening was broken down into two stages and all screening was undertaken by RO. The first stage, which included all studies discovered during the searches and reviewed against the criteria summarised in Table 2, articles were screened at title and abstract level to determine which articles were relevant for a full review. At title and abstract level, it was difficult to determine the direction (positive or negative) of any reported impacts and therefore, studies reporting impacts on social and or environmental processes were retained in the first stage of screening. Articles’ full text were then imported and articles without full texts available were excluded. Subsequently, a full text screening was performed to refine the articles based on applicability to a UK context and articles describing negative consequences to social, economic and/or environmental systems. The range of articles included were from 2010 to 2020. These dates were chosen to align with the initial and growing interest in developing bio-based economies as part of the European Bioeconomy strategy (Paternmann and Aguilar, 2018).

The second stage of screening involved two criteria; firstly, in order to bound the scope of the study based on ecosystem characteristics, study countries were selected based whether they overlapped with either of two large marine ecosystems (LMEs): Celtic-Biscay Shelf and the North Sea. Secondly, articles were refined to only those which described potentially negative consequences from seaweed aquaculture to surrounding social, economic and or environmental systems. In order to extract a list of negative consequences as described in selected article a checklist of prompt questions relating to environmental, social, and economic systems was used during the screening of full text articles. Effects that were considered as a yes response to any of the questions listed below were extracted from the articles and used later at the coding and extraction stage.

**Prompt questions**

1. Does the described effect have the potential to perturb ecosystem functions including abiotic functions for example climate regulation,
or does it have the potential to damage and reduce the abundance of biodiversity including fauna and flora?

2. Does the described effect introduce interference, conflict or risk to stakeholders using marine resources in economic activities?

3. Does the described effect create interference, conflict or risk to social communities and stakeholders outside the area of economic activity?

### 2.3. Coding and data extraction

To ensure that data extraction from the final list of articles was systematic, a codebook was built and used to create a catalogue of articles and described impact(s). Data types extracted and the format in which data was extracted is provided in Table 3. Impacts were separated based on which domain was impacted by seaweed aquaculture: Environmental (biotic and abiotic components), Social, and Economic. The codebook was designed to also capture general information on the studies such as the article title and reviewer details.

#### 2.3.1. Causal Diagrams explaining potential negative consequences to social, economic, and environmental dimensions

Extracted data (Table 3) was used to create a catalogue of evidence from which causal diagrams were created. The aim of these causal diagrams is to improve understanding of, and highlight potential negative consequences to, social, economic, and ecological processes, from expanding seaweed aquaculture inside a wind farm area as part of an MUS. The causal diagrams are proposed as a baseline for further Integrative Assessment and Modelling-based research on this topic and in assisting in the management of SA development inside Wind Farms. The impact pathways were based on information extracted from the articles. Overlapping impacts from differing sources were joined into causal pathways based on related impacts. Plus and minus symbols were used to indicate directionality of change between variables in the impact pathways. The causal diagrams were created using Vensim PLE x64 software. The main diagram was separated into environmental and social-economic impacts for illustrative purposes.

### 3. Results

#### 3.1. Systematic literature review summary

A total of 1984 articles were identified during the initial search. After duplicate removal and first stage of screening a 175 articles remained that included a description of an effect of seaweed aquaculture on social, environmental, and economic systems. After the second screening a total of 17 articles were left (Fig. 3). The decline from 175 to 17 results was attributed to the North-West Europe specification and refinement to only negative consequences, that were included into the second screening stage process.

The 17 remaining articles ranged in format, including scientific journal publications, books, and reports from governmental and academic institutions. Articles assessing the social and ecological impacts of offshore seaweed aquaculture were limited to qualitative research methods only, including, literature reviews and expert consultation (n = 2). Most impacts that were described derived from studies of nearshore seaweed aquaculture using the long-line technique (cultivation of seaweed using a rope-like material extending along a water column, anchored to the seabed and suspended by buoys) (n = 9). The method of cultivation was undefined, or unknown, in the remaining cases (n = 8).

The Miah et al. (2020) report produced from the EU-funded MacroFuels project and SAMs (2019) Seaweed Farming feasibility study for Agyrll & Bute, both provided the largest sources of recorded impacts with 10 impacts extracted per report. Although, seaweed species were undefined in several articles, Sugar Kelp (saccharina Latissima) was the most frequently cited species evaluated (n = 8), potentially resulting from interest in biofuel development and a native species to North-West Europe. Less frequently identified species included Purple Laver (Porphyra umbilicalis) (Rhodophyta), Darweed (Laminaria digitata) (Phaeophyceae), Dulse (Palmari palma) (Rhodophyta), Sea lettuce (Ulva lactuca) (Chlorophyta) (n = 3). A full summary of the impacts extracted is provided in the supplementary materials (“Codebook and Data_SA NEW (2) (1).Exl”) and detailed in the following sections. Subsequently, these impacts were used to illustrate a range of negative consequences that may stem from developing seaweed aquaculture inside of Wind Farms in the LMEs of the UK and were used to develop initial framework(s) for further IAM studies.

#### 3.2. Potential consequences to the environment

There are several causal factors for why different components of the SA installation inside of Wind Farms may cause negative impacts to the functioning of local ecosystems. We divide environmental impacts into two parts: six impact pathways perceived to derive from the seaweed cultivar itself and four impact pathways caused by the seaweed farm infrastructure and its associated maintenance. See Figs. 4 and 5 for a visual representation of these pathways which are described in the following paragraphs.

Firstly, a report by SAMs (2019) and study by Grebe et al. (2019) describes the bottlenecking of genetic diversity in natural seaweed populations caused by the increase in the abundance of domesticated seaweed species that have reduced genetic variation and the potential for hybridization of this material into natural seaweed populations from escaped sporophytes. Moreover, the genetic diversity of natural seaweed populations may also be reduced during the setup or maintenance of the farm due to overharvesting of wild sorus tissue (Grebe et al., 2019).

Marine ecosystems may also be threatened by disease and pest outbreaks either due to the intentional and accidental cultivation of non-native species into an ecosystem or the placement of new artificial and biotic surfaces that facilitates the dispersal of species between disparate habitats (Miah et al., 2020; Badis et al., 2019; Wood et al., 2017).
Fig. 3. Workflow schematic for the Systematic Literature Review with articles outputted during each stage of the review process.

Fig. 4. Chain of events leading to negative impacts on environmental systems from seaweed biomass during cultivation inside wind farm array.
The net primary productivity of photosynthetic organisms in an ecosystem may also be reduced in the event(s) of increased nutrient competition and light attenuation extending from the seaweed biomass (surface area and density), causing a trophic cascade of reduction in the total marine biomass stock, including planktonic and benthic zoo-plankton, and animal communities such as fish (Benson et al., 2014; SAMS, 2019; van den Burg et al., 2020a; Miah et al., 2020; Wood et al., 2017).

Biodiversity levels may decline further as a result of increases in the mortality rate of avian species, due to the increased levels of trophic activity and seabird predation in the area increasing collision potential with the turbines of Wind Farms (van den Burg et al., 2020a). In the Macrofuels Sustainability Assessment Report (2020), potential escalation in the mortality rates in benthic biodiversity were identified as a result of the hypoxic/ anoxic conditions created in the rising concentrations of particulate and dissolved organic matter lost from the seaweed farm (SAMS, 2019; Grebe et al., 2019).

Another feature recognised in the deployment of SA is wave attenuation, which lead to reductions in hydrodynamic flow and turbulence of surface currents (Bruhn et al., 2020). As a result, there is a downstream impact in the form of diNOflagellate blooming as well as general disturbance to phytoplankton communities (Brown et al., 2020; SAMS, 2019).

Four articles also raised concerns about the placement of infrastructure as possible sources for marine mammal entanglement, and/or the loss of synthetic material that may be ingested by organisms as well as associated increases in boat traffic creating displacement effects with respect to marine fauna and flora (SAMS, 2019; van den Burg et al., 2020a; Miah et al., 2020; Gegg and Wells, 2019).

Finally, some of the articles reviewed described disruptions to ocean-atmosphere regulation that stems from the emission of climate active gasses. A study by Wood et al. (2017) and Hasselström et al. (2018) observed that the release of volatile gases such as iodine compounds, can lead to cloud formation and changes in local weather.

3.3. Potential consequences to society including economic and non-economic impacts

Seaweed aquaculture inside of a Wind Farm also contains potential to create adverse impacts to both economic and non-economic elements of social systems. These impacts can be divided into two types. Firstly, four impact pathways are drawn from the seaweed farm infrastructure and its associated maintenance. Local community conflict may manifest through several pathways (Fig. 6). For example, the visual and noise pollution that results from increased boat traffic was highlighted to disturb the aesthetic values communities place on coastal and marine areas and, consequently, this decreased the recreational value of the area (Hasselström et al., 2018). Another source of community conflict resulted from the loss of synthetic material from the farm itself leading to possible damages to maritime activities (Miah et al., 2020). Industrialisation of rural areas alongside the influx of seasonal agricultural workers and increased traffic were also effects considered within the SAMS report (2019) and may reduce public acceptance of the seaweed industry and further intensify community conflict (Gegg and Wells, 2019).

In the sustainability assessment report produced by Miah et al. (2020), health and safety issues leading to increased labour market risk potential were identified as a concern due to the nascenty of the seaweed aquaculture sector in Europe and therefore, a lack of operational experience for the European sector compared with other regions such as Asia. Coastal and marine stakeholders were also subject to adverse impacts in two of these social-impact pathways. SA installations led to increased claims on available space which was hypothesised to create spatial competition and interference across environmental protection objectives, fishery operations and leisure uses (Hasselström et al., 2020; Gjertsen et al., 2020; Miah et al., 2020; Gegg and Wells, 2019; Hasselström et al., 2018).

Secondly, two impact pathways were considered that resulted from the seaweed culitvar itself. For example, nutrient competition and light attenuation alters ecosystem dynamics which in turn reduces fish biomass, thus lowering yields in fisheries catch rate resulted in increased conflict with fisheries-based stakeholders (Fig. 7) (Préat et al., 2018; Clavelle et al., 2019). Lastly, changes in environmental conditions, including increasing pH and Dissolved Oxygen Levels which promotes corrosion of steel structures may lead to enhancement of biofouling maintenance costs (Fig. 7) (van den Burg et al., 2020a).

4. Discussion

Successful promotion and implementation of the multi-use setting concept relies on elucidating all the impacts (negative and positive)
of MUS designs across all three sustainability dimensions: social, economic, and environmental (van den Burg et al., 2020b). The Systematic Literature Review approach allowed us to undertake a logical review of the current evidence available on the potential negative consequences of promoting SA inside Wind Farms resulting in causal diagrams (Figs. 4–7) to explain the potentially negative event sequences to biodiversity and ecosystems and economic and non-economic stakeholder interactions. The findings from the review outline a wide range of potential impacts encompassing each pillar of sustainability, including potential conflicts with biodiversity protection agendas, deprecating values for cultural and natural heritage and decreasing economic values of community activities (Bracco et al., 2019).

The systematic review also indicates that significant consideration should be made to social problems that may stem from developing a SA-Wind Farm system. For example, the suggestion to develop SA within a wind farm system was a proposed as a measure to overcome spatial conflicts with existing marine users, such as fisheries, in the nearshore setting (Buck et al., 2017; Abhinav et al., 2020). However, the causal diagrams demonstrate that moving to a MUS does not necessarily minimise the existing conflict with these users and may simply transform the conflict pathway instead (Fig. 7). The studies by Preat et al. (2018) and Clavelle et al. (2019) revealed that in the event of light attenuation and nutrient competition, the reduction in marine biomass would lead to a loss in fishery yields and reduce the economic viability, that without compensatory economic measures, would put fishery stakeholders at a loss. The inclusion of social variables, as proposed in the causal diagrams, thus further improves sustainability analysis by incorporating social and economic components that are often subject to exclusion in evaluations of bioeconomic innovations (Székács, 2017; Gawel et al., 2019).

Our approach illustrates the complexities associated with the multiple effects observed within and across the three-pillars of sustainability.
and provides more detail than traditional approaches to assessing sustainability in bioeconomic systems management. For example, lifecycle assessments (LCA), have been performed for sustainability assessments of a macroalgal-biofuel supply chain (Seghetti et al., 2016; Aitken et al., 2014). However, such approaches typically exclude critical metrics for holistic sustainable development, i.e. wider environmental and social-economic impacts, as they only account for one objective of the sustainable development goals: namely, mitigation of climate change caused by current energy consumption and related greenhouse gas emissions (GHG) (United Nations, 2015). Neglecting additional environmental variables from sustainability assessments misrepresents the complexity found within ecosystems and, as a consequence, creates the possibility of inaccurate conclusions being drawn.

To illustrate, the causal diagrams illustrate a potential pathway, through which SA within MUS may reduce existing marine biomass (Figs. 4 and 5). This occurs due to the cultivated seaweed potentially out-competing other photosynthetic organisms therefore reducing the primary productivity of an ecosystem (Benson et al., 2014; SAMS, 2019; van den Burg et al., 2020a; Miah et al., 2020; Wood et al., 2017). As a result, this may lead to an overall reduction in the total marine biomass in the system concurrently also reducing carbon sink levels—otherwise known as “blue carbon”—of an ecosystem (Macreadie et al., 2019; Thompson et al., 2017; Benson et al., 2014). However, this is only one potential pathway and the cumulative influence of multiple impact pathways may amplify the effect of reduced total marine biomass stock (Figs. 4 and 5). In contrast, although the LCAs demonstrate a reduction in climate change impacts of the biofuel supply chain they fail to recognise complex feedbacks that can lead to increased climate emissions through other pathways such as ecosystem change and carbon flux.

Once causal diagrams have been established, a range of integrative assessment modelling methods can be applied to address the uncertainty surrounding the outcomes resulting from the development of a SA-Wind Farm system. For example, a knowledge-based model may be used to evaluate the operational performance of the SA-Wind Farm system at set scales within a specific territorial boundary (Kelly et al., 2013), such as techno-economic assessment evaluating the required scale of aquaculture production needed for an economically feasible seaweed product supply chain. Bayesian Network analysis may then be implemented to determine the likelihood of negative events, highlighted in the systematic review and visualised in the causal diagrams, from occurring, such as nutrient competition between the cultivated macroalgae species and local photosynthetic organisms (Kelly et al., 2013). Thus, the results of combining causal diagrams with IAM, may be used to define a safe operating space with regards to balancing environmental sustainability objectives alongside optimised benefits gained from deploying seaweed aquaculture within Wind Farms (Campbell et al., 2019).

The causal maps highlight the need for further development of integrated assessment and modelling research methods to ensure that the inherent trade-offs in these MUS are managed appropriately within the emerging SA-Wind Farm bio-economic system. Integrating social, economic, and environmental objectives into a single assessment, such as proposed here in our causal diagrams, provides a foundational framework for interdisciplinary research collaboration and management that may improve understanding on the complexity of social-ecological interactions with the emerging SA-Wind farm bio-economic system. The study attempts to counteract the reductionist approach often used in analyses of the Bioeconomy transition by implementing a holistically sustainable evaluation, covering environmental and social-economic interactions, during the initial construction of a novel bioeconomic system (Wohlfahrt et al., 2019; Székács, 2017; Urmetzer et al., 2020), with potential to apply to other novel technologies proposed under the Bioeconomy.

The review demonstrates the need for interdisciplinary collaboration due to the range of influence seaweed aquaculture has across multiple dimensions including social, economic and ecological elements. The systematic review and causal diagrams are a preliminary step to begin to structure and design integrative cognitive models that will facilitate a better understanding of the impacts of introducing SA within Wind Farms to social, economic and ecological systems that extend from this bio-based activity. The application of a cognitive modelling approach to developing the causal diagrams was an attempt to advance the application of probabilistic and Knowledge-Based analyses to address uncertainty in developing SA inside a wind farm. However, the information used for the causal diagrams was drawn from evidence sources with a large spatial variability that necessarily influence the probability of events and accuracy of the relationships proposed. Moreover, the articles used to define the relationships in the frameworks were derived from studies that addressed slightly different questions and contexts. The specific impacts and their likelihood will be highly dependent upon the circumstances in which the SA takes place, such as type of SA installation and associated practices including management, scale of production, ecosystem dynamics and social circumstances of a region. For example, some studies in the review were based on a nearshore cultivation context, thus spatial conflict with stakeholders was included within the causal diagrams (Fig. 6), however, this pathway may become redundant in offshore circumstances due to the stakeholder exclusion occurring inside Wind Farms and distance from coastal marine activities (Abhinav et al., 2020).

It is important to note that the high levels of uncertainty on the relationships and likelihood of impacts means the causal diagrams proposed cannot be considered final frameworks for analysis, nor do they guarantee specific events will occur. Instead, they should be considered to illustrate possible outcomes and pathways and should be used to justify the need for further evaluation of SA within MUS, based on inter-disciplinary collaboration to develop model variables and relationships, prior to undertaking quantitative assessments. The causal diagrams should be used as initial frameworks to collect data and account for negative event sequences when managing pilot trials of SA-MUS. We argue that the use of causal diagrams coupled with further IAM techniques will complement more reductive sustainability models, such as LCAs, by integrating additional biophysical variables and quantitative analysis and can be used to support decision-making and management.

It is recommended subsequent analyses on the topic use a hypothetical case study to restrict the variability found in LMES and coastal communities across North-West Europe. This includes defining the features and components of the SA-Windfarm biosystem such as the infrastructure and seaweed aquaculture practices, scale (spatial and temporal) and location. The causal diagrams may then be further developed using the combined expertise of interdisciplinary panel(s), for example, using a facilitated cognitive modelling technique to reveal further impacts that were not described in literature, however, perceived. Accessing group-based judgement and a diversity of mental models on the topic will be important to ensure cognitive and or publication bias affecting the results of this study are removed (Burgman et al., 2021). The broad and complex nature of the topic led to a decision in the review process to limit the evidence focussed on negative consequences-only. However, access to a collaborative network also overcomes resource limitations experienced in this study and further research using a collaborative approach can attempt to balance both positive and or negative within the evaluation to improve understanding for decision-making and future modelling applications. The advantages and disadvantages found through the literature review process of integrating seaweed aquaculture inside Wind Farms are broadly summarised in Table 4.

Recent management innovations generated at the interface between Bioeconomy and Sustainability research argue that inter-disciplinarity within the modelling and assessment of bioeconomic activity is fundamental in order to ensure that sustainability targets are met (Wohlfahrt et al., 2019). The Systematic Review and Causal Diagram approach proposed here provide immediate outputs for the understanding of SA development inside Wind Farms. More broadly, they can be considered as a starting point for testing and constructing novel IAM techniques for ensuring holistic sustainability of emerging innovations.
within other bioeconomic systems (Wohlfahrt et al., 2019). Thus, they may be used as decision-making tools that can be deployed to ensure multi-dimensional sustainability within an applied setting of the Bioeconomy transition.

5. Conclusion

The systematic review provides the latest synthesis of evidence regarding economic, social, and environmental impacts of Seaweed Aquaculture development inside Wind Farms. The integration of Seaweed Aquaculture inside Wind Farms from a technical perspective appears highly possible given successful offshore seaweed aquaculture trials and support, and further research is desirable given the development opportunities the multisite setting possesses. The MUS is a promising solution to spatial conflicts within the Blue Economy and there has been much interest in the positive benefits of SA; however, the results from the review indicate that trade-off analyses will be required to determine optimal operating conditions and scales if developments were to proceed. The evidence catalogue created here includes data sourced from qualitative and quantitative sources, and varying contexts that can support evaluations and management of SA-Wind Farm pilot trials to ensure that wider environmental and social-economic impacts are considered. The approach proposed in this study provides a means to broaden existing sustainability assessments in order to take into consideration social and ecological impacts of bio-based development strategies. The causal diagrams outlined are illustrative of the possible impacts that need consideration in promoting SA-Wind Farm biosystems. These causal diagrams should be built upon through further analyses and combined with probabilistic and knowledge-based modelling which would elucidate further impacts and potentially alleviate some of the uncertainty of the likelihood and consequences SA development inside Wind Farms. Such an approach would enable holistic sustainability assessments, that consider all three pillars of sustainability, for other novel management techniques and innovations within the Bioeconomy transition. Holistic sustainability is fundamental if the Bioeconomy transition is to be successful and the systematic review and causal diagrams presented here provide the first step in delivering upon this requirement.

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 undertaken by main author.

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.


