
Using Decision Science and Bioprocess Engineering for Sustainable Innovation
- A case study of the Offshore Multi-use Setting

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Thesis Submitted for the degree of Doctor of Philosophy

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December 2023

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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*, 100559, (8) DOI: 10.1016/J.ENVCL.2022.100559

Preprint under revision at *Journal of Environmental Management*:

O'Shea et al., (2023) "Managing offshore Multi-use Settings: use of conceptual mapping to reduce uncertainty of co-locating seaweed aquaculture and wind farms", version 1 available at DOI: 10.21203/RS.3.RS-3009526/V1

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Acknowledgements

Alex and Caroline, your supervision throughout the MSc and my PhD has been outstanding. I could never imagine the position I am in today without your guidance. Thank you for your encouragement, mentorship, critical reflections, and expertise and giving me the academic freedom that led to this work. I indebted to you both and hope our work together continues. Thank you to all those who advised on my project, where Bill, Elisa, Victoria, Kok Siew, James and Xiaotao, you've been immensely helpful, and this thesis would not have been possible without your guidance. Every conversation that sparked new ideas and results will always be remembered. Similarly, I am indebted and hope this is the beginning of our work together and not the end.

Thank you to all my former and current colleagues and friends at CEP and beyond. From serious work discussions and almost never-ending rants about the world to the moments of constant laughter, it's an experience I will forever value. A special thanks to my Vancouverites, Herman, Dylan, Nathan, Krista, Liam, Tilda, and Abi, it's been emotional. As proof that I'm weird and what you'd expect of someone who writes a thesis involving seaweed: thanks Dot, you're a great companion and it's shame you will never understand this sentence because you are a dog.

And thanks to my family for your support over the years. Gemma and Russ, thank you for continuing to believe in me and I will continue raiding your fridge and need you to buy my clothes, but I promise to pay you back from now on. Lastly, Erika, thank you for all your support and enriching my life so much, ti amo.

Abstract

The Blue and Circular Bio-based Economies are positioned as approaches to tackle 21st century social and environmental challenges. However, the development and management of innovations must satisfy multiple objectives (economics, social and environmental) in the pathway to a sustainable future. The task of ensuring holistic sustainability induces complexity in the decision-making process and is seldom considered in its fullest sense. To address this problem, this thesis uses a case study of the multi-use setting of seaweed aquaculture within wind farms to explore the use of integrative assessment and modelling techniques drawn from decision science and biological engineering to support the management of early-stage, bio-based innovation. More broadly, demonstrating an approach to account for the multidimensional nature of sustainable innovation.

A systematic review of the literature first enabled the assessment of early-stage innovation of co-locating seaweed aquaculture and wind farms, against social to environmental objectives. Following a literature review, a hypothetical case study of developing seaweed aquaculture inside a North Sea wind farm is created. This is then used to explore the potential consequences of such a development using conceptual mapping combined with evidence synthesis and structured expert elicitation. Insights are presented as causal diagrams and impact tables of the case study outcomes within social, economic, and environmental domains. The findings of conceptual mapping demonstrate the broad range of potential risks and benefits to co-locating seaweed aquaculture and a wind farm including biotic and abiotic enhancements and deterioration, economic opportunities and disruption, and benefits and conflict with social communities in the region.

This thesis uses the information captured in the causal diagrams and impact tables to evaluate environmental sustainability trade-off and risks of seaweed production inside a wind farm. Alongside the risk assessment, a techno-economic assessment and strategy is devised for feasible implementation of the concept.

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Chapter 1

Introduction

1.1. Offshore Multi-use Setting and Uncertainty in Decision-Making

The marine economy is predicted to grow at double the rate of the mainstream economy by 2030 (European Commission, 2021) and consequently competition for marine resources will increase in the coming decade(s) (Hodgson et al., 2019). A key question will therefore be around how to increase efficiency as well as resource and space-sharing amongst multiple users. The offshore Multi-use Setting (MUS) is a proposed innovation that aims to promote efficient use of space in the marine economy by either co-locating industrial activities (Abhinav et al., 2020). Seaweed aquaculture, located inside of wind farms, is a promising MUS-type system (Abhinav et al., 2020; Buck et al., 2018). As they are fixed-structures, wind farms supposedly result in the exclusion of other marine stakeholders, such as large fisheries and shipping. Consequently, by including seaweed production 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).

Seaweed Aquaculture (SA) involves the cultivation of macroalgae, photosynthetic organisms that are distributed in marine ecosystems throughout the world (García-Poza et al., 2020). As macroalgae contain a range of compounds that meet food/feed, cosmetic, nutraceutical, pharmacy, fertiliser, and energy needs, they can be considered a highly valuable renewable resource, which is the main driver for growth and increasing attention in seaweed aquaculture (Balina et al., 2017). Although seaweed aquaculture offers many potential benefits, concerns about the environmental and social impacts of co-locating seaweed aquaculture inside wind farms have been raised (van den Burg et al., 2020a). However, the concerns about SA within a MUS, and the MUS concept more generally, are mostly speculative and the impacts are uncertain (van den Burg et al., 2020a; van den Burg et al., 2020b). This is due to limited empirical evidence from pilot studies and knowledge on the topic alongside the complexity of the impacts. Nonetheless, the uncertainty of consequences hinders development of concept of seaweed aquaculture within an MUS (van den Burg et al., 2020b) and prevents advancing a potentially valuable production system 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 are reduced to understand advancing the innovation that has been proposed (Bröring et al., 2020).

Furthermore, the development of an industry based on seaweed falls more broadly within the 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 (Araújo et al., 2021; Fritsche et al., 2020; von Braun, 2018). The SCB, otherwise known as the “Bioeconomy”, broadly represents an amalgamation of biotechnology and scientific knowledge within the political objective of using existing and new biological resources in a “sustainable and economic way” (Aguilar et al., 2019). The Bioeconomy can fit within the same normative position as the Sustainable Development Goals (SDGs) which infers that activities within it are managed to contribute to the objective of balancing environmental, societal, and economic goals, such as those also outlined by the SDG framework (Aguilar et al., 2019; European Union, 2018; Gawel et al., 2019). This presents an additional challenge, such that the impacts of seaweed aquaculture development must be contextualised within the overarching objective of sustainability to provide a holistic management procedure, which is currently lacking.

To satisfy the multidimensional nature of sustainability within decision-making and engineering of bio-based innovations, integrative assessment and modelling (IAM) is a key approach that can be used across multiple levels and scales of process development(s) and help to reduce uncertainty in innovation management (Bakshi, 2019; Kelly et al., 2013). IAM broadly refers to analytical techniques common to systems science, engineering and environmental management to connect and understanding the social, technical and/or natural features of a particular space – be it environmental or technological (Hamilton et al., 2015; IPCC, 2014; Sayer et al., 2001). Integrated models can also be used in simulations to explain, and/or predict, the behaviours of a system across spatial and temporal gradients (Ewert et al., 2013). The information sought from IAM is useful to aid the management process in instances where empirical data may be restricted (Kelly et al., 2013). Moreover, the IAM approach employs “systems thinking”, defined by Arnold and Wade (2015, p. 675) as the following:

“Systems thinking is a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviours, and devising modifications to them in order to produce desired effects. These skills work together as a system.”

Implementing a systems thinking approach can enable the complexity of situations to be better accounted for by acknowledging the interactive nature of environmental, social and economic domains and consequentially, mitigates limitations of the reductionist perspectives to natural resource management (Sternier et al., 2019; Virapongse et al., 2016). Furthermore, systems thinking in human-nature relations emphasises the embedded context of society in ecosystems, and thus the critical interdependencies between the two domains, and how the evolution of one is shape by the other (Folke et al., 2016; Reyers & Selomane, 2018).

With the uncertainty surrounding the impact of a MUS, taking an IAM approach covering social, economic and environmental domains will be needed to aid decision-making (van den Burg et al., 2020b; Wohlfahrt et al., 2019). The information produced from an IAM approach can be used to characterise the potential consequences of MUS development to help gain community support (van den Burg et al., 2020a). This includes addressing knowledge gaps by identifying impacts- beneficial and negative- of MUS schemes and making practical management recommendations to mitigate detrimental effects that may occur. Moreover, the sustainability implications of MUS impacts must be further evaluated and enhance decision-making towards supporting social-ecological sustainable outcomes as directed by Circular Bioeconomy policies (Aguilar et al., 2019). A summary of the conceptual linkages between policy and innovation proposals in addition to sustainability metric is shown in **Figure 1**.

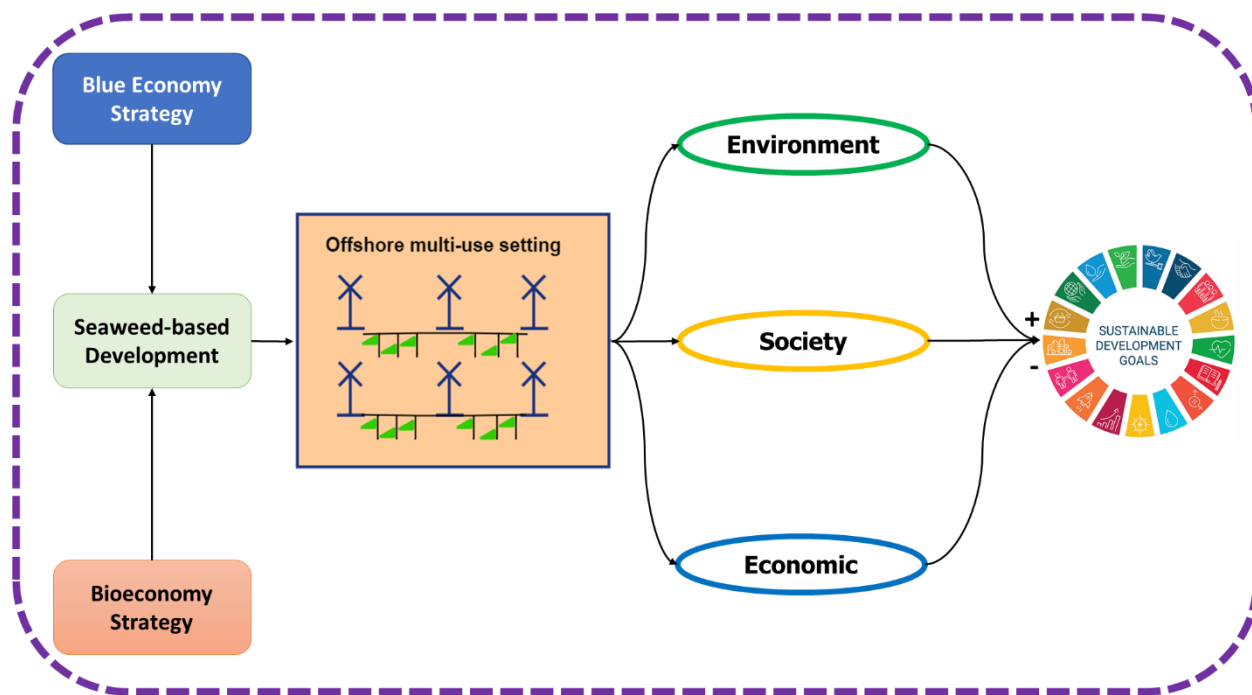


Figure 1- Schematic summarising conceptual linkages between Blue Economy and Bioeconomy strategies stimulating seaweed-based development and the MUS and the sustainability implications of said developments.

1.2. Problem Statement

The offshore MUS has the potential to deliver economic opportunities whilst encouraging efficient use of space within the marine economy. Co-location of seaweed aquaculture and wind farms is a promising offshore MUS design. As an innovative mechanism within the Circular Bioeconomy, the establishment and management of MUS systems is required to meet the objectives of sustainability (social, economic, and environmental) and must therefore enhance social-ecological conditions whilst also providing economic benefits, as defined by frameworks, such as the United Nations Sustainable Development Goals. However, there is limited understanding of the integrated impacts across sustainability dimensions (social, environmental, economic) associated with MUS activities which limits designs for such systems and is a major barrier to the further development and holistic management of the concept of offshore MUS.

Furthermore, there have been limited studies that account for multiple sustainability objectives, through the application of integrative assessment and modelling to biosystem proposals within the Circular Bioeconomy. As such, alongside understanding the sustainability impacts of new technologies, such as SA within a MUS, we must also concurrently further develop and evaluate the use of methodologies that are capable of assessing the multiple sustainability dimensions within early-stage bio-based innovations.

1.3. Aim and Objectives

This research aimed to investigate the sustainability consequences of developing seaweed aquaculture inside wind farms to provide management recommendations for implementing MUS within the Circular Bioeconomy transition. It also aimed to review, and further develop, the use of the integrated assessment and modelling approach/ techniques to evaluate the sustainability of Circular Bioeconomy innovations more broadly. The specific objectives were:

- a) To investigate the identified impacts of seaweed aquaculture development and explore potential outcomes associated with the offshore MUS system.
 - A systematic literature review was performed to search and collate evidence relating to the impacts of seaweed aquaculture development on surrounding landscapes. The findings were used to identify potential negative consequences that may result from seaweed aquaculture development inside a wind farm within the North Sea territory. The findings were presented in the form of cognitive maps (visual mental representation of a situation by an individual/group) explaining the source and pathway to the final impacts to social and ecological systems.
- b) To explore the potential impacts across social, economic, and environmental objectives of seaweed aquaculture development inside a wind farm and construct conceptual maps to facilitate further integrative assessment and modelling techniques using a combination of horizon scan, group-based cognitive mapping, and evidence synthesis in a hypothetical case study.
 - A combined Delphi method and cognitive mapping methodology was used to identify the potential social, environmental and economic consequences - positive and/or negative - of developing seaweed aquaculture inside Hornsea Wind Farm over the next ten years (a hypothetical MUS scenario). Suitability of Hornsea was determined owing to the theoretical feasibility of developing seaweed aquaculture within existing Turbine arrays at the site based on existing evidence. The results were structured into impact tables describing the perceived effects coupled with conceptual maps explaining the influence of seaweed aquaculture on social-ecological systems. The implications of the

methodology and findings were critiqued in the boarder context of management in the Circular Bioeconomy.

- c) To identify and evaluate environmental sustainability trade-off and risk potentials of developing seaweed aquaculture inside of a wind farm using the findings from objective b, sustainability trade-off assessment and evidence synthesis
 - An environmental sustainability trade-off and risk review was performed on the perceived impacts generated from objective b and the from the hypothetical case study of Hornsea Wind Farm. The findings were presented in the form of impact tables aligned with a sustainability objective and cognitive maps. Moreover, the identified trade-offs were characterised using evidence synthesis to understand the risk potential of each trade-off against the objectives of the Sustainable Development Goals.
- d) To develop a techno-economic strategy for integrating seaweed aquaculture inside of wind farms using the findings from objective b, C-K design theory- a methodology exploring conceptual and known knowledge spaces in the design of a system-, and techno-economic assessment- a profitability analysis of an activity over time- combining process simulation and discounted cash flow analysis in Microsoft Excel
 - A techno-economic assessment was performed to evaluate the potential design of a seaweed biorefinery meeting technical and sustainability specifications derived from the hypothetical MUS case study of objective b. A process model was built and used to biological, technical and economic characteristics of the process system and enable discounted cash flow analysis. The findings included a biorefinery design proposal, process simulation and profitability potential of different scenarios using the seaweed biorefinery system. Moreover, the findings were used to discuss a process development strategy for the offshore Multi-use Setting.
- e) Review the methodological process and make recommendations for holistic sustainability assessment of early-stage innovations.

1.4. Structure of Thesis

This thesis has three main themes:

1. The impact uncertainty of seaweed development inside wind farms.
2. The relationship of the Multi-use Setting development to the objective(s) of sustainability.
3. The value of the methods used, and findings, as a contribution to improving the assessment and management processes applied to biosystem innovations in the Circular Bioeconomy transition.

The thesis first introduces in Chapters 1 and 2 the background information relating to the topic of offshore MUS including why the MUS was proposed, the problems surrounding the uncertainty of consequences and how management objectives are derived. Chapters 3 and 4 are initial explorations identifying the potential impacts of a MUS case study, namely, developing seaweed aquaculture inside a North Sea based wind farm (Objectives A and B). The aim of this section was to explore the topic by identifying the positive and/or negative impacts from SA in MUS systems across sustainability objectives given specific spatial and temporal boundaries. Additionally, findings were presented as cognitive maps to structure information and enable further decision-making techniques including risk/ sustainability assessments and techno-economic modelling (process design, simulation, and profitability analysis) and thus inform holistic decision-making if promoting seaweed aquaculture within wind farms. Chapter 5 evaluates the environmental sustainability trade-off and risk of the impacts identified in Chapter 4 to further characterise the consequences and provide management recommendations under uncertainty and need for sustainable decision-making in light of the environmental sustainability risks I identified (Objective C). Chapter 6 uses information from the Chapter 4 to support decision-making through process system design, modelling and techno-economic assessment (discounted cash flow analysis) and builds on previous recommendations in the development of seaweed aquaculture inside a wind farm (Objective D). Chapter 7 combines the findings from the previous chapters to provide a critical review of the integrative assessment and modelling process that was used in relation the development of the Multi-use Setting and specific problems within the topic. The IAM process is then linked to related, broader concepts in renewable energy, Circular Bioeconomy and management approaches targeting the sustainability objective. Chapter 8 provides a summary of the work and

recommendations for future work (Objective E). The structure of the thesis is summarised below in **Figure 2**.

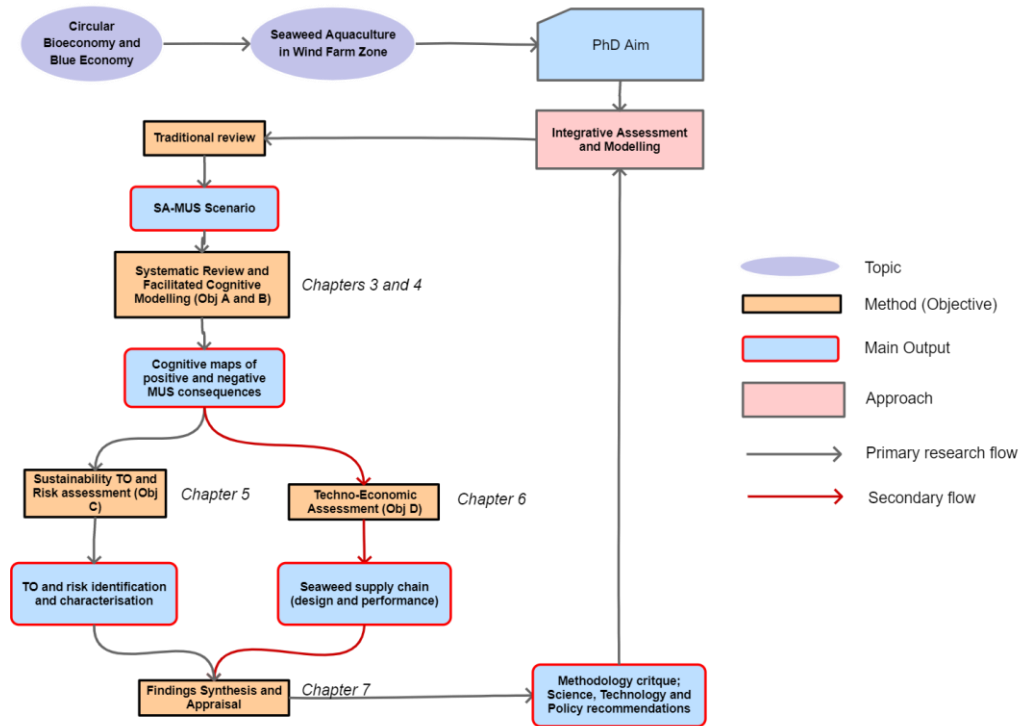


Figure 2- Schematic outlining the thesis structure and stages including methods, main outputs and the related objectives of the work. TO= trade off.

Statement of original contribution

This research presents a novel approach to investigating the consequences of developing a MUS type system and provides management recommendations accounting for sustainability using a combination of techniques drawn from the fields of decision science and biological engineering. Moreover, the thesis addresses the broader gap in the literature relating to the Circular Bioeconomy transition and the need for holistic (social, economic, and ecological) sustainability assessment methodology to be conducted on bio-based innovations and developments. The thesis is the first integrative assessment that uses advanced cognitive mapping techniques that limit bias and promote validity of predictions on the outcomes of a systems change, within the context of the MUS. To-date potential positive, neutral, and negative consequences of developing seaweed aquaculture inside of wind farms were largely unknown and speculative. However, this thesis identifies the potential outcomes across social, economic, and environmental domains. The research also structures information on the impacts that can facilitate further decision-making techniques that were not possible owing to the lack of qualitative structures i.e. conceptual maps and impact tables, to support management in real-life systems with a reduction in uncertainty surrounding consequences of project developments. The thesis also contributed further to the topic of the offshore MUS as it systematically identifies the environmental sustainability trade-offs and risks that could result from the integration of seaweed aquaculture and wind farms. These risks and trade-offs can impose environmental limitations on an innovative proposal (SA in a MUS) and these risks were previously undisclosed in the literature.

The use of decision science process/techniques also revealed the need to temporarily shift focus away from the offshore MUS and devise and evaluate a strategy to make offshore seaweed production techno-economically feasible in the first place. Application of biological engineering techniques and utilising the information sourced from decision science fulfilled said need. This thesis presented the first design and assessment of industrial process system that can theoretically scale and extract value from seaweed as production increases into the offshore setting whilst meeting green manufacturing principles. The biological engineering research also resulted in a novel conceptual process with far reaching implications in the renewable energy transition, namely, a means for techno-economic performance optimisation of clean power technologies with the ability to incentivise greater investment via the coupling

with (macro)algae processing. All of which was unknown until the IAM approach of this thesis was proposed and applied.

The approach and findings of this thesis have also made a novel contribution to the Circular Bioeconomy literature relating to the evaluation and management of bio-based innovations accounting for social, economic, and environmental objectives during implementation and scale-up that is seldom performed. This thesis presents the first attempt to incorporate multiple objectives and evaluate sustainability implications in the conceptual phase of a bio-based innovation to provide sustainable management recommendations under uncertainty. This work has been submitted and published in scientific journals, presented at conferences, and created a spinout enterprise securing sponsorships from Innovate UK EDGE and the Biorenewables Development Centre (EU regional development grant). The thesis was primarily conceptualised, developed, and executed by me. Support with thesis ideation, methodologies critique, analysis and structure were provided by Dr Caroline Howe and Dr Alexandra Collins. Dr Elisa Capuzzo provided technical advice on offshore seaweed aquaculture during Chapter 4 and development of a hypothetical case study for the Multi-use Setting. Dr Victoria Hemming provided methodology critique for Chapter 4. Dr Kok Siew Ng and Professor Xiaotao Bi provided methodology critique for execution of Chapter 6 alongside technical insight of bioresource technologies with Professor James Clark.

Chapter 2

Background

The literature review provides contextual background to the concepts and topics of this thesis. The section starts at the macrolevel including societal challenges, the objectives of sustainability and policy responses aiming to support the achievement of sustainable development. The following sub-section then focuses in on marine ecosystems and emerging socio-economic features and the importance of innovation and marine spatial planning in this space. The offshore Multi-use Setting is then described, and the problems associated with development of Multi-use Setting type systems.

2.1. Development challenges and Policy Responses

The development challenges facing society in the 21st century are complex and stem from significant changes in environmental and social conditions that have occurred over the last century or so. The use of fossil fuels in dominating the energy system has resulted in severe changes to the climate as a consequence of amounting carbon dioxide (CO₂) emissions (IPCC, 2018). The rising global temperatures and changing climatic patterns has caused a cascade of effects across all global ecosystems. Temperature gradients are shifting resulting in a change in how organisms may invade new habitats that may have detrimental consequences, for example the spread of disease in native populations (Turbelin & Catford, 2021). The changing climate is also leading to more frequent droughts and desertification, leaving wildlife populations lacking in food and water resources and shifting productivity rates (Weiskopf et al., 2020). Contemporary environmental change and degradation is further complicated by the range of pressures being placed on ecosystems. A non-exhaustive list of such pressures includes continuing habitat fragmentation from resource extraction, unabating nutrient and chemical pollution, the over-exploitation of species and introduction (deliberate and accidental) of non-native species, all of which are leading to the damage and/or loss of biodiversity at exponential rate and with it, the ecological functions provided for life to exist and thrive (IPBES, 2019; Loucks, 2021).

Adjacent to the environmental challenges are persisting and proliferating social challenges. Living standards have risen globally over the past 100 years as evidenced by declining poverty rates and increasing average life expectancy (Canudas-Romo, 2010; Sullivan & Hickel, 2023). Medical advances have been made to treat a range of ailments that were once considered incurable. Nonetheless, the gains are not felt universally across human society and many of the advances made are being compromised and long-term issues are still present owing to a complex mix of factors such as increasing inequality both with respect to financial and non-financial aspects (Koh, 2020). Furthermore, food insecurity is still present for large proportions of the world's population and is predicted to increase further and inflict many more with malnourishment (Mirzabaev et al., 2023). The aging populations of developed economies will put greater pressures on already strained health services and infrastructure and at the same time, economic stagnation is becoming prevalent in many of the same regions (Knapp & Somani, 2008; Tymoigne, 2022).

The social and environmental issues faced by societies are, however, very rarely isolated and the complexity of these issues extends in part from the intertwined nature of social and ecological factors (Wei et al., 2018). Development challenges must thus be considered holistically, accounting for the social and environmental domains across time and space (Weber et al., 2021). Sustainable development is the leading response to global development challenges underpinned by the holistic goal of achieving sustainability – minimising and limiting the trade-offs between social, economic, and environmental objectives.

The concept of sustainability was promoted by the Brundtland report in 1987 and the phrase “meeting the needs of the present without compromising the ability of future generations to meet their own needs” is regularly cited as the original definition (Brundtland, 1987). Since the Brundtland report, the objective of sustainability has been further defined/ characterised including how it may be measured and achieved. A major development in the philosophy of sustainability was made by the United Nations (UN) with the proposal of the Sustainable Development Goals (SDGs) in 2015, a collection of social, economic, and environmental sub-objectives with related targets and indicators to guide and measure progress towards achievement of sustainability (Hajian & Kashani, 2021; United Nations, 2015). For example, the sub-objectives focus on improvements to terrestrial and marine ecosystems including conservation of habitats and halting biodiversity loss, the removal of nutrient pollution and preventing further damage in marine ecosystems; promoting efforts for mitigating and adapting to climate change; improving the economic conditions of nations such as sustained, inclusive

growth and decent work in addition to reducing inequality (financial and gender); reducing poverty rates and increasing access to nutrition and providing quality education. A critical feature of the SDG framework was also the need to consider the social, economic and environmental sub-objectives holistically and prevent trade-offs between the domains meaning one objective cannot be secured at the expense of another- as directed by goal 17- “partnership for the goals” (United Nations, 2015). The realisation of the SDGs presented a significant step in the evolution of the philosophy and science of sustainability, presenting a framework to guide societal processes towards a supposedly definable and measurable objective(s) and has become the purpose of various activities since its conception in 2015 (Hajian & Kashani, 2021).

The objective of sustainability influences society at all levels, from management including government policy and regulations, to the behaviours of individuals and businesses, alike (Agrawal et al., 2022; Geissdoerfer et al., 2018). An industrial concept known as the Sustainable and/or Circular Bioeconomy, or otherwise referred to as the Bioeconomy¹, is a coordinated attempt to progress society towards greater social-ecological sustainability (Aguilar et al., 2019). The Circular Bioeconomy is largely affiliated with biotechnology and bioprocessing and general advancements in scientific knowledge, within the political objective of using existing and new biological resources in a “sustainable and economic way” (Aguilar et al., 2019). Interest in developing a Circular Bioeconomy is seen throughout the world with dedicated policies and strategies found in several nations including Global North including the USA, United Kingdom, and European Union members and the Global South including Brazil, Colombia, India, Malaysia, Mexico and more (**Figure 3**) (Bioökonomierat, n.d.; Birner, 2017)

¹ The “Bioeconomy” has multiple meanings- see Vivien et al (2019) for explanation on the alternative uses of this term. For this thesis, it is assumed as the biotechnological concept i.e. “Type III Bioeconomy”

Bioeconomy Policies around the World

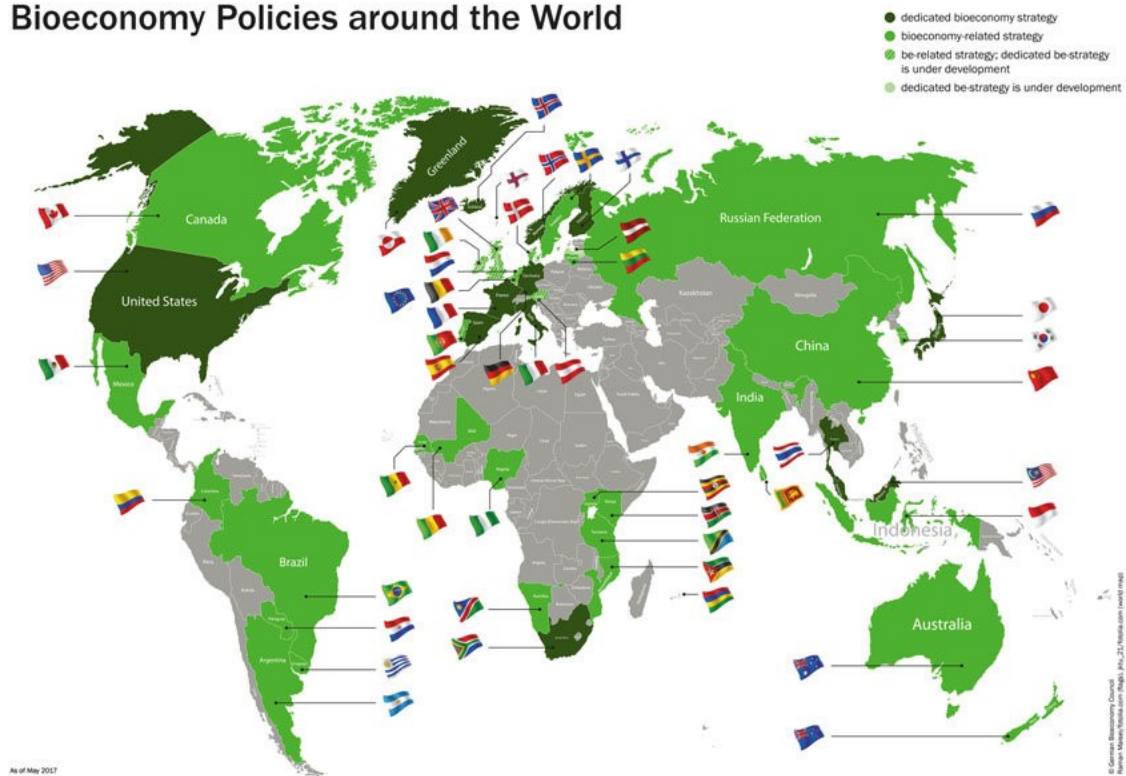


Figure 3- A map of countries- highlighted in green- with Bioeconomy-type policies and strategies developed by national governments, collected from a review in 2017 by the German Bioeconomy Council, Bioökonomierat (Birner, 2017). Figure extracted directly, with no edits from Birner (2017).

The notion of a Bioeconomy arose from the growing body of knowledge about the natural world and accompanying developments in biotechnology and bioprocesses whereby biological organisms, systems and/or processes are exploited from a technical perspective to improve human wellbeing (European Commission, 2018; Patermann & Aguilar, 2018). A Bioeconomy proposes that sustainability can be achieved by basing economic activity on renewable (biological) feedstocks which are potentially inexhaustible over time compared with activities reliant on non-renewable inputs (European Commission, 2018). The types of economic activity based on biological feedstocks and processes are already diverse, including products for energy, food, and health markets. Proponents of the Circular Bioeconomy argue for further economic expansion based on novel bio-based innovations creating new products and potentially new markets (European Union, 2018). Moreover, it is believed bio-based resources can “circularised” in the economy meaning the waste from one activity is valorised by another

and thus increasing the material flow and economic lifecycle of an organism/ biomass for longer (Kershaw et al., 2020). The Circular Bioeconomy is also endorsed as a method to reduce the carbon emissions into the atmosphere as biological organisms are classed as renewable carbon feedstocks to, firstly, promote carbon sequestration from the atmosphere and secondly, used to displace fossil-based counterparts with the claim of creating a carbon neutral or negative supply chain (González-Garay et al., 2021).

On the other hand, the claimed sustainability advantages of the Circular Bioeconomy are contested, as common management practices used in biosystem developments may be insufficient to achieve sustainability and, in some cases, even amplify rates of social-ecological degradation (Egenolf & Bringezu, 2019; Wohlfahrt et al., 2019). The development of bio-based innovations is an important feature of the Circular Bioeconomy, however, this is situated within the broader environmental and social context that is rarely considered, if not, completely neglected in bioprocess development(s) (Bakshi, 2019; Székács, 2017). For example, substitution of fossil fuels with bio-diesel made from oily crops is a leading alternative for combustion engines (Chia et al., 2022). Nonetheless, switching to a bio-based counterpart doesn't necessarily enhance social-ecological sustainability if the bioeconomic supply chain results in a loss to social welfare such as inducing resource conflict among local communities, and/or reduction in native ecological habitats for crop production (Gawel et al., 2019; Jeswani et al., 2020). Assessments considering the biophysical basis of a transition to a Circular Bioeconomy have also recognised that, depending on the use cases of biomass, simply switching existing resources with a bio-based counterpart such as fossil fuel to biofuel, will only further accelerate ecological degradation owing to the rates of consumption far exceeding the renewal capacity of ecosystems (Giampietro, 2019).

The challenge of sustainability within the Circular Bioeconomy lies at the management level, as bioeconomic developments are not adequately evaluated in terms of a holistic consideration of environmental and social factors, with a greater emphasis placed on the technical and economic domains (Székács, 2017; Wohlfahrt et al., 2019). Even in cases where environmental dynamics are considered, these tend to focus on a few selected metrics such as carbon emissions of the process and neglect the ecological dynamics thus reducing the accuracy of claims about sustainability (Gawel et al., 2019; Urmetzer et al., 2020). Consequently, such reductionist perspectives for advancing biotechnologies and bioprocessing will mean that it is impossible to determine where trade-offs and risks lie across the three domains of sustainability.

Improving the management of bioprocess developments and the Circular Bioeconomy overall, can be done using integrative assessment and modelling (IAM) tools that link the technology and economic aspects of a biosystem with the wider environmental and social context (Gawel et al., 2019; Issa et al., 2019). The aim of using IAM is to create information that supports more holistic management by improving the understanding of the wide-ranging outcomes that may result from a proposal such as scaling up bioproduction and effects to the landscape ecology (Elsawah et al., 2020; Pyka et al., 2022). IAM tools work at multiple levels from the “micro-level”, namely, evaluating a single process or macro-level such as the combination of activities within a set territory. Thus, they can better inform management decisions by accounting for the multidimensionality of complex systems development and are therefore, more closely aligned with the requirements of sustainability criteria (Forsberg et al., 2016; Pyka et al., 2022). It is important, therefore, that evaluations within the Circular Bioeconomy include the use of dedicated integrative assessment and modelling methodologies and consider the case study specific needs for supporting the decision-making process of bio-based innovations (Pfau et al., 2014; Wohlfahrt et al., 2019). Although, many emerging biotechnologies and their management procedures will benefit from IAM applications, marine biotechnology processes are promising options for supporting the resource needs of society- energy, food and medical- and bypass many of the drawbacks of their terrestrial equivalents (Lee & Lavoie, 2013; Rotter et al., 2021)

2.2. Marine Ecosystems and Socio-Economic Development

The marine environment is complex. Ecosystems are open- with varying degrees of connectedness between organisms and ecological communities- and with different ecological dynamics exhibited across latitudinal and longitudinal gradients, from coastal habitats to offshore and deep-sea environments, all unique in terms of their biotic and abiotic features (Carrasco De La Cruz, 2021; Danovaro et al., 2017; Murphy et al., 2021). The seas and oceans have played an integral part of human evolution and well-being (Buonocore et al., 2020) with marine habitats contributing to “ecosystem services” whereby ecological functions create conditions for human life to thrive (Buonocore et al., 2021; Mynott et al., 2021). The ecosystem services provided by marine systems are classified into *provisioning* - the biophysical products (energy and mass) obtained from a habitat such as food; *regulatory* - the

benefits of regulating natural processes such as the climate; *supporting* - basic ecological functions such as nutrient cycling and *cultural* - the intangible benefits humans of nature such as aesthetic value (Buonocore et al., 2021; Milcu et al., 2013).

Today, the marine environment hosts major industrial clusters that contribute significantly to regional economies (Stebbing et al., 2020). The major existing industries are fisheries, with fish totalling over half of all vertebrate species in wildlife trade and equating to 180 billion US dollars as of 2018 and 11% of animal protein consumption (European Environment Agency, 2019; Lambert et al., 2022) and ports and shipping which account for 50% of global trade in value terms and is considered the backbone of global trade in goods (Verschuur et al., 2022). There is also the fossil fuel sector with offshore operations responsible for a ¼ of all oil and gas supply (International Energy Agency, 2018) whilst considerable value is drawn from leisure and tourism associated with the coastal regions and seas (Stebbing et al., 2020). However, the role of marine resources as economic goods and services, are expected to increase even further in the next decade and see greater contributions to human development (OECD, 2016). The predicted value of the marine economy, defined as all commercial activities associated with marine systems, will reach three trillion dollars by 2030 (HM Government, 2017). The reason behind the rising ocean value stems from factors such as technological innovation meaning greater access to marine resources and linked economic opportunities and dedicated policies encouraging or supporting further extension of the marine economy (European Commission, 2020; Martínez-Vázquez et al., 2021). Although many existing activities may expand as shown by projections in the marine transport sector at least doubling from 2010 by 2035 (Walsh et al., 2019), meeting different government objectives from food security to renewable energy and Net Zero it can be expected that many other emerging sectors will increase in significance (Bax et al., 2021; Lee et al., 2020).

The ambitions to replace fossil energy sources is predicted to cause a rapid expansion of offshore renewable energy technologies and infrastructure as governments attempt to meet Net Zero by 2050 - meaning no net carbon emissions into the atmosphere from economic activity by 2050 (Hevia-Koch & Jacobsen, 2019; International Energy Agency, 2021). Wind farms sited in offshore regions i.e. away from land and coastal areas, is advocated as an optimal solution to generate renewable energy with favourable conditions for maximising energy yields (Barooni et al., 2022; Dincer et al., 2021) and bypassing the social barrier of “NIMBYISM”, a phrase used to capture the rejection of visually displeasing projects by local residents (Bates & Firestone, 2015; Susskind et al., 2022a)

Offshore wind farms are under continual development, with the global pipeline for installations reaching over 100 GW of added capacity and Governments such as the UK, having ambitions for up to 50 GW of offshore wind power production by 2030 (HM Government, 2023; RenewableUK, 2023). However, added technical innovations are becoming commercialised and are facilitating the growth in the production of renewable energy from marine environments. Floating wind turbines are a promising design that means wider access to areas of the sea that were previously considered economically infeasible using existing fixed pylon designs (Barooni et al., 2022). In addition to advancing wind technologies, tidal turbine power systems are accelerating, offering distinct advantages as a more constant and predictable energy supply and presenting lower risks to marine life (Shetty & Priyam, 2022). The current capacity of tidal power is markedly lower in the renewable energy mixture (International Energy Agency, 2022). However, tidal turbine technologies are relatively less mature than other renewable energy technologies (wind turbines and solar panels). Nonetheless, scale-up of tidal power system(s) is expected to occur and several organisations are emerging with tidal turbine innovations that aim to advance cost effective operations, increasing market capitalisation of marine energy sector (International Renewable Energy Agency, 2020.; Orbital Marine Power, n.d.) Although, renewable energy production is expected from the marine environment, energy storage and transmission solutions will also be necessary and developments including hydrogen infrastructure and increased grid connectivity, will also increase claims within the marine space (Tosatto et al., 2022).

Alongside the expansion of the energy industry at sea, aquaculture - the farming of selected marine species (fish, bivalves and aquatic plants) - is likely to grow (Klinger et al., 2018). Significant interest in the sector is becoming widespread with existing production focused in Asia and newer interests at the global scale (García-Poza et al., 2020; Jespersen et al., 2014). Aquaculture opportunities are being capitalised outside traditional Asian countries with nearshore farming being seen in coastal areas of Europe and America and several government schemes are looking to propel the industry further with developments in offshore aquaculture systems and coupled processing (Buck et al., 2017; Buschmann et al., 2017; van den Burg et al., 2019). Lastly, completely novel technologies may also emerge add to the industry load with artificial intelligence, for example, enabling autonomous vehicle applications, or Deep-Sea Mining for precious minerals (Chen et al., 2022; Niner et al., 2018). However, in spite of the socio-economic possibilities, the seas and oceans already face extensive pressure from anthropogenic activity that has resulted in the degradation of ecological networks and loss of

ecological function and these potentially new threats may compound the issues (Claudet, 2021).

2.3. Changing Oceans and the Blue Economy

Human activities are inextricably linked to the evolutionary dynamics of marine environments and human-induced impacts on oceanic ecosystems risks the continuity of both social and ecological marine systems (Jouffray et al., 2020; Levin, 2015). Fisheries are over-exploiting target species and causing mass decline in fish stocks, in addition to general degradation of marine habitat, therefore threatening entire ecosystems with extinction (Botsford et al., 1997; Pauly et al., 2005). The loss of fish biomass is not only problematic for communities dependent on fisheries for their livelihoods, but the loss of biomass downgrades ecological networks overall with compounding effects to ecosystem integrity and climate change through loss of once sequestered carbon (Cinner et al., 2012; Gao et al., 2016). Another major concern is the rise in chemical pollutants in coastal waters and beyond that has arisen from unabated fertiliser use on land with run-off into waterways eventually leading to marine zones (Kiedrzyńska et al., 2014; Tornero & Hanke, 2016). As a result, the excess nutrients (nitrogen, phosphorus and potassium) increase the potential of eutrophication whereby algal blooms occur and destabilise the ecological system due to hypoxia/ anoxia of the waters (Hupfer & Hilt, 2008). Chemical pollution, however, extends much further capturing everything from plastic (micro and macro) to caffeine, medicines etc., all carrying negative implications to the functions of aquatic ecosystems (Bellas et al., 2020; Fong & Ford, 2014; Thushari & Senevirathna, 2020). These are but a few examples of the immense pressures pervasive within the marine environment and without intervention, will only grow in severity. Therefore, the socio-economic advancements expected, based on currently available marine resources must actively seek to either limit any further damages to ecosystems or ideally, promote ecological restoration where possible (Claudet, 2021).

The Blue Economy is a concept proposed to account for the growing capacity of value extraction from the marine environment which concurrently encourages socio-economic development in the marine space but mandated on meeting all three sustainability objectives (Kaczynski, 2011; Okafor-Yarwood et al., 2020). The concept encapsulates existing economic activity including, but not limited to, fisheries, shipping, oil and gas, in addition to newer

industries such as renewable energy (offshore wind and tidal), marine aquaculture, marine biotechnology, ecological restoration and so on (OECD, 2016; Vieira Veríssimo et al., 2021). The Blue Economy is already claiming to tackle a wide range of 21st century challenges from securing food security to supply of renewable energy with the interventions listed above (Vieira Veríssimo et al., 2021). To realise the Blue Economy, policy instruments are being extended from the concept to leverage governmental support in terms of research and development, funding, and programmes of social networks to facilitate the transition (Cisneros-Montemayor et al., 2021; Kaczynski, 2011). However, the anticipated interventions are not free from trade-offs and will carry risks to the surrounding social and ecological systems (Hodgson et al., 2019). For example, a concept known as deep-sea mining, whereby technology is used to procure materials stored in deep-sea ocean floors, is being explored and advocated for supplying rare materials to the economy (Miller et al., 2018). On the other hand, deep-sea mining has been identified to cause significant damage to deep-sea ecosystems and results in a loss in ecosystem structure and services that support human life (Niner et al., 2018; Orcutt et al., 2020). Fish aquaculture despite having strong potential to contribute to food security needs, is commonly associated with pollution downstream of farming sites and the spread of pests both within the cultivated region and the wider environment (Martinez-Porchas & Martinez-Cordova, 2012; Shakouri & Yazdi, 2012).

The complex development of the Blue Economy and potential problems arising across social and ecological dimensions necessitates coordination and management solutions at the macro-level. Marine spatial planning (MSP) is a tool used to consider human activities across space and time within marine zones (Frazão Santos et al., 2019). The purpose of MSP is to balance a set of activities within an area and optimise the social and ecological objectives by coordinating each group of relevant parties (Ehler et al., 2019). The use of MSP reveals an immediate social challenge within the Blue Economy that is, with increasing number of operations within the marine space there will be greater competition and user conflicts in accessing resources (Young, 2015). It will therefore be a priority to implement solutions that reduces the likelihood of spatial conflicts and maximise value to all relevant parties (Cisneros-Montemayor et al., 2021). Chief among such solutions are the offshore Multi-use Setting (MUS) and Multi-purpose Platforms (MPP) (Bijma et al., 2013; Ford et al., 2022).

2.3.1. Offshore Innovation

The Multi-use Setting (MUS) and Multi-purpose Platform (MPP) are closely related planning and design engineering concepts to help reduce spatial claims within the Blue Economy. They are advocated as a promising solution to reduce the issues of spatial constraints on economic activities at sea by combining production systems within the same space (Jansen et al., 2016; Steins et al., 2021). The MPP-type system aims to use a physical platform that will contain multiple operations in a designated area offshore including: renewable electricity generation; energy storage and transmission facilities such as hydrogen infrastructure, and biomass production and processing (**Figure 4**) (Nassar et al., 2020)

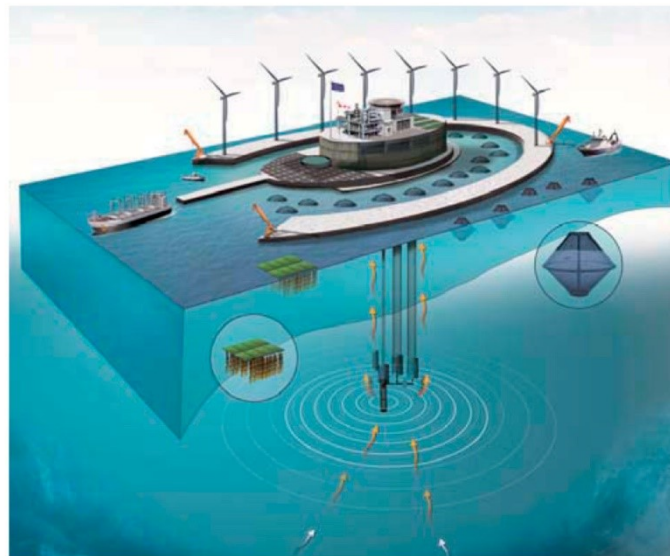


Figure 4- Visual graphic of offshore Multi-purpose Platforms combining energy and biomass production and processing at sea- figure extracted directly, with no edits from Nassar et al (2020).

Similarly, the offshore MUS aims to co-locate marine industrial activities within the same space (Schupp et al., 2021). The possibility for an offshore MUS result from the exclusionary nature of Wind Farm arrays (Abhinav et al., 2020; Steins et al., 2021). 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 alternative industries within these zones, it

is possible to utilise space that would otherwise not be used by other marine stakeholders, thus reducing competition for marine spatial resource of emerging activities (Abhinav et al., 2020). The types of activities being targeted for integration with wind farms include low and high trophic species aquaculture and tourism, with preliminary testing initiated for the MUS (North Sea Farmers, n.d.; Przedrzymirska et al., 2021; van den Burg et al., 2020b).

Although, the immediate advantage of the MUS is efficient use of space, the MUS system has also been pitched as a solution to several 21st century development issues. To illustrate, the rising carbon levels caused by the combustion of fossil fuels changes the climate with significant threats to human well-being (Lelieveld et al., 2019; Smith et al., 2014). Greenhouse gas levels therefore need significant reduction, and an energy system with minimal-to-negative carbon emissions must replace the existing infrastructure (DeAngelo et al., 2021; Fuss et al., 2020; Gielen et al., 2019). Offshore Wind Farms (OWF) are a favourable option for generating low carbon renewable energy as they contain advantages in costs and energy supply stability (Hevia-Koch & Klinge Jacobsen, 2019; Sun et al., 2021). Nonetheless, to achieve the decarbonisation targets set by Governments, wind farm operations will need to be scaled up (Aunedi et al., 2021).

Although, OWF potentially provide a renewable energy supply with reduced carbon emissions, they still host environmental and social challenges. The impacts of wind farm developments may include, but are not limited to, noise pollution, displacement of aquatic species, mortality of biodiversity such as marine mammals and birds, chemical pollution of waters and changes to the aesthetic values of an area (Bailey et al., 2014; Copping et al., 2020). The consequence of these cumulative social and environmental impacts is the potential for lower social acceptance and challenges in regulators permitting licenses to wind farm developments (Copping et al., 2020). The result is hindered progress towards achieving a decarbonised energy system. To overcome regulatory barriers and stakeholder acceptance of developments, a Social License to Operate (SLO) is used whereby a score based on the socio-economic and environmental performance is given to a development that corresponds to a level of “social acceptance” (Hall et al., 2013). The formations of an offshore Multi-use Setting may improve the SLO score of wind parks as the placement of certain activities improve social and environmental conditions (Schupp et al., 2021). For example, aquaculture of extractive species such as bivalves and seaweed, is associated with increasing the supply of ecosystem services to communities (Hasselström et al., 2018; Hughes, 2021). Eco-tourism is also another sector emphasised in the design of the MUS (Bocci et al., 2019; Schupp et al., 2021) and is attributed

with socio-economic benefits such as local income opportunities, in addition to conservation of biodiversity (Khanra et al., 2021; Stronza et al., 2019). Therefore, the individual or combination of activities added to the wind farm array is hypothesised to improve SLO scores and thus support wind farm consenting.

Despite the advantages of using the offshore MUS as a mechanism for development, the MUS remains just that, a concept. European Union sponsored projects have been performed to progress the MUS, however, barriers exist for operationalising the idea (van den Burg et al., 2020a). The hurdles to actualising the MUS include perceived and/or real social problems that remain unaddressed and furthermore, research is needed on MUS designs that demonstrate positive outcomes across economic, environmental, and societal objectives (van den Burg et al., 2020b). Until the social and ecological uncertainties surrounding the MUS activities are alleviated, it is likely progress will remain slow with a risk to the innovation falling into the “valley of death” whereby innovative ideas do not actualise (Ellwood et al., 2022; van den Burg et al., 2020b). Alleviating the uncertainty surrounding social and ecological consequences caused by MUS designs is needed to advance the offshore innovation that has been proposed. Furthermore, the outcomes of project developments must be considered in terms of contributions to sustainability meeting broader managerial objectives of the Circular Bioeconomy/ Blue Economy transitions (Cisneros-Montemayor et al., 2021; Lee et al., 2020; Lokko et al., 2018). To that end, an integrative assessment and modelling approach covering social, economic, and environmental objectives is required to provide information that supports the decision-making process on integrating industrial activity offshore within the same space.

Chapter 3

Exploring Evidence and Introducing IAM to the Multi-use Setting

3.1. Introduction

Offshore Multi-use Settings have been proposed as a mechanism to maximise the resource benefits derived from a specific marine region with one example being offshore wind farm arrays (Abhinav et al., 2020; Steins et al., 2021). Although wind farms exclude traditional stakeholders, aquaculture- the farming of marine organisms- is an emerging sector in Europe and is a key activity targeted for integration with Wind Farms for the transition to a MUS system (Schupp et al., 2021). To progress the synchronisation of wind farms and seaweed production, the consequences will need better characterisation to support decision-making including understanding negative effects/ risks (van den Burg et al., 2020a). However, consequences are largely speculative and uncertainty and require a systematic methodology to improve on accuracy of impact predictions.

Aquaculture, otherwise known as mariculture, is a method of biomass production aiming to meet a variety of needs including biofuels to the supply of food and other high value products (Balina et al., 2017; Fraga-Corral et al., 2022). Aquaculture is typically sited nearshore (Lester et al., 2018), however, this presents a challenge in scaling up production in areas such as Europe, as aquaculture activity exerts pressures on the surrounding environment resulting in stakeholder opposition and thus, constrains the levels of cultivation (Hofherr et al., 2015; Troell et al., 2013). Offshore aquaculture provides a potential solution. Offshore aquaculture may be defined as aquaculture infrastructure sited in more exposed conditions with a higher energy environment (Buck et al., 2018; Froehlich et al., 2017). The advantages of moving further offshore include reducing pressures on coastal ecosystems from aquaculture development and accessing a significantly larger area for cultivation (Buck et al., 2018; Kim et al., 2019; Lester et al., 2018). Accessing larger cultivation areas is required for the supply of certain products such as biofuels, as economic viability is not feasible at the current rate of production (Gegg & Wells, 2019). Support for the idea of offshore aquaculture has resulted in several developments in ensuring offshore aquaculture feasibility including infrastructure, operating protocols and regulations (Buck et al., 2017; Froehlich et al., 2017; NOAA, 2016). Despite interest in

offshore aquaculture, costs of production are high and stakeholder opposition is still a key concern (Buck et al., 2018; Holmer, 2010).

Combining Wind Farms and aquaculture as a form of MUS provides a potential pathway to address some of the implementation issues facing offshore aquaculture. The key advantages claimed include minimising potential for marine stakeholder conflict owing to the reduced presence of stakeholders inside Wind Parks, the larger areas available for production offshore and opportunities for cost sharing with Wind Farm operators (Buck et al., 2018). Co-location designs for extractive species and Wind Farms have been considered but not yet actualised (Buck et al., 2017). Extractive species include bivalves, that are filter-feeding molluscs found extensively in different aquatic environments (Canesi & Pruzzo, 2016) and seaweed, also known as macroalgae, where macroalgae are photosynthetic organisms that are distributed in marine ecosystems throughout the world (García-Poza et al., 2020).

Operationalising the Multi-use Setting concept, initially, with extractive species, particularly seaweed, may be pragmatic for multiple reasons. Firstly, seaweed aquaculture (SA) is considered to have lower levels of environmental impacts during cultivation (Visch et al., 2020) and trials of SA in the North Sea have demonstrated infrastructure that is deployable in the offshore environment (Buck et al., 2017; Buck & Buchholz, 2004). Furthermore, protocols are available for transferring brown seaweed species aquaculture to offshore conditions (Buck et al., 2018). Lastly, expanding SA 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).

Despite the potential benefits arising from the integration of seaweed aquaculture inside Wind Farms, potential risks to the environment and human health have been raised (van den Burg et al., 2020a). Social support is key to the feasibility of projects, and lack of support for the development of seaweed aquaculture within an MUS limits implementation (van den Burg et al., 2020a). It has been found that unsustainable use of environmental resources can derive from the dominance of a reductionist perspective in natural resource management whereby discipline-focused individuals, driven by their own perspective or objectives, such as economics or conservation, will vary the outcome of a development based on the view of designated managers (Pascual & Howe, 2018). As a result, different “winners and losers” scenarios are created, with economic development often being the dominate focus and

generating a lack of incentive towards meeting environmental objectives. Understanding the key concerns related to social and ecological consequences of seaweed aquaculture-wind farm system can help to overcome this reductionist perspective, identify concerns early in a project, and improve the chance of providing innovative solutions and modification to better address these concerns. To that end, integrated assessment and modelling (IAM) could help reveal and subsequently better manage the social and ecological impacts of Multi-use Setting designs (Abhinav et al., 2020).

Integrative assessment and modelling (IAM) broadly refer to analytical techniques common to systems science and environmental management to connect and understanding the social and natural features of a space (Hamilton et al., 2015; IPCC, 2014; Sayer et al., 2001). Therefore, IAM may help to understand the impacts generated in the move towards a Multi-use Setting System (van den Burg et al., 2020b). Applying the IAM approach to understand the social and ecological interactions of SA expansion inside Wind Farms and to address uncertainty in decision-making can be done using several common modelling methods ranging from probabilistic to dynamic simulation, depending on the type of information being sought and the available data (Kelly et al., 2013). However, an initial step for moving to quantitative models is the process of developing qualitative cognitive models or maps (French, 2021; Kelly et al., 2013). The process seeks to define cause and effect relationships, entities and preferences (French, 2021).

Nonetheless, to the best of the author's knowledge, no existing frameworks had 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 Chapter 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.

3.2. Methodology: Systematic Review

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 environmental 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 thesis and therefore, the review focussed 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 & Adams, 2020). LMEs are coastal and ocean areas with ecologically definable characteristics and boundaries (Belkin et al., 2009) which allowed me to bound the study to ensure that only relevant information was captured. For example, impact analyses of tropical climates 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 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 **Figure 5**. The full library can be found in supplementary materials.

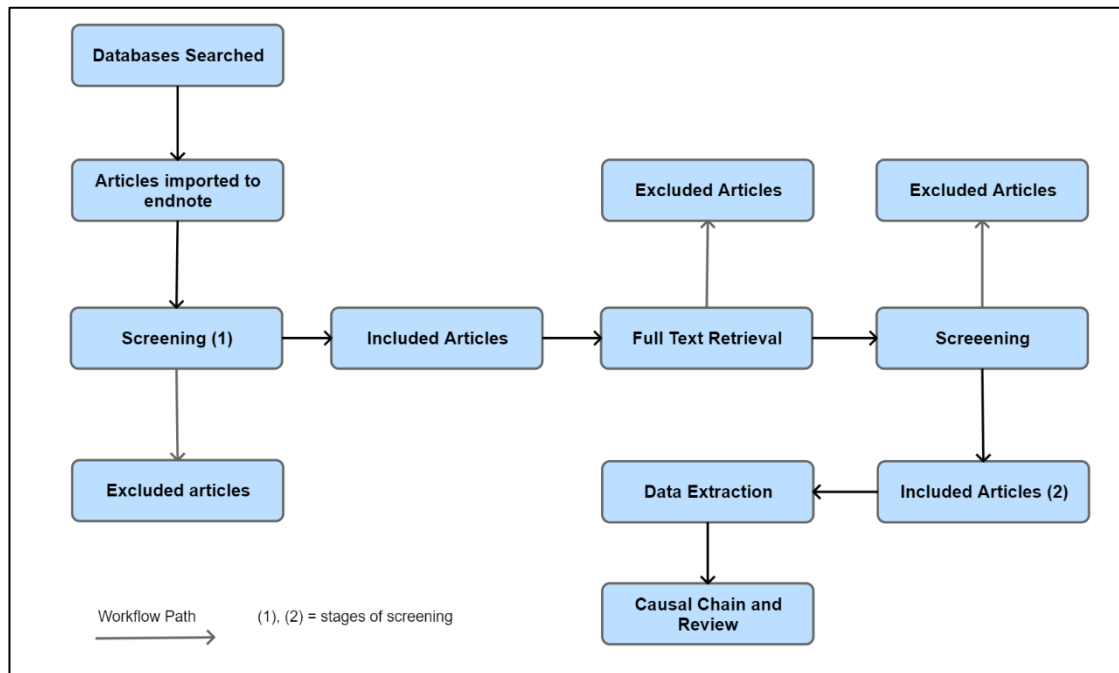


Figure 5- Workflow detailing the different stages of the systematic review of the literature on potential adverse consequences to environmental and social dimensions caused by development of seaweed aquaculture inside Wind Farms

3.2.1. 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. 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 related 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 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 made, see Table 21 and Table 22 in the supplementary materials. An initial search was performed using the location string one in Table 21. 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.

3.2.2. 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.

Table 1- PICO table for rapid evidence assessment of social and environmental impacts of seaweed aquaculture in North-West Europe

Question	<i>What are the potential negative consequences to social and environmental systems from developing Seaweed Aquaculture in a UK/North-West European context?</i>
Population Subject or unit of study	Coastal or Marine social and environmental systems in North-West Europe: United Kingdom, Norway, Sweden, Denmark, Netherlands, Belgium, France, Germany and Republic of Ireland
Intervention The proposed management regime, policy or related intervention/ exposure applied or investigated	Seaweed Aquaculture
Comparator The control with no intervention or an alternative to the intervention	Area prior to Seaweed Aquaculture being practiced
Outcome The effects of the intervention	“Negative consequences” or “adverse impacts” to social, economic and/or environmental systems during seaweed aquaculture

Screening was broken down into two stages and all screening was undertaken by Ryan O’Shea (RO). In 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. The full text of the remaining articles 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 (Patermann & Aguilar, 2018).

Table 2- Table detailing the inclusion and exclusion criterion used during screening in the systematic review.

Inclusion	Exclusion
Articles assessing effects or impacts of seaweed aquaculture on environmental or social systems e.g. changes to biophysical or economic processes in the region	Articles not assessing Seaweed Aquaculture focused environmental or social system impacts e.g. articles detailing wild harvesting effects were excluded as the scope of analysis is seaweed aquaculture-only, articles describing or assessing Microalgae species; cyanobacteria, diatoms and - technical applications for downstream products using Seaweed Biomass were also excluded
Data accepted from any domain; economic, social and/or environmental	Papers describing or assessing Microalgae species, cyanobacteria and diatoms.
Article must be discussing in the context of, or applicability to UK farming, countries and regions include: Greenland, Maine, New Brunswick, Nova Scotia, New Foundland, United Kingdom, Republic of Ireland, Belgium, the Netherlands, France, Germany, Denmark, Norway, Sweden, Iceland	Articles focusing on application outside the targeted regions and countries
Articles must be in English	Articles in languages other than English
Articles from 2010 – present	Articles prior to 2010
Articles are accepted from all organisations- academia, non-governmental, government and business- providing they meet other eligibility criteria.	
All publication types	
Abstract must be available	

Full text available	Unable to access source of full text through journal databases or University resources
Papers assessing negative effects/ impacts extending from seaweed aquaculture to social, economic, and environmental systems	Papers assessing positive or neutral effects
Articles study area or context must be within/ applicable to the following nations: United Kingdom, Norway, Sweden, Denmark, Netherlands, Belgium, France, Germany and Republic of Ireland.	Articles focusing on application unapplicable to North-West European region

The second stage of screening involved two criteria; firstly, 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. 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?*

3.2.3. 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.

Table 3- Details of types of information extracted from the final list of articles related to adverse impacts of nearshore and offshore seaweed aquaculture in North-West Europe

ID	Seaweed Aquaculture	Format	Notes
1	Aquaculture type	Text	Offshore or Nearshore
1.1	Aquaculture Method	Text	e.g. long line, fixed structure
1.2	Farm size	Unit	Hectare or km ²
1.3	Aquaculture species	Text	Common and Scientific Name
1.4	Data source	Text	e.g. Laboratory, survey, simulation, live farm
1.5	Assessment	List	Quantitative or Qualitative/ Mixed method
1.6	System impacted	List	Economic, Social or Environmental
1.7	Response variable	Text	Variable(s) impacted by SA description of effect/change to system process
1.7(i)	Units-RV	Text	Unit of measure for response variable
1.8	Explanatory Variable	Text	Cause of change to system
1.8(i)	Units-EV	Text	Unit of measure for Explanatory Variable
1.9	Correlation	List	Increase or decreases response variable
1.9(i)	Formularised	List	Y/N; formula?
1.9(ii)	Formula	Text	Formula for relationship
	Additional comments	List	
ID	Bibliographic information	Format	Notes
2.1	Location	Text	Country of study or Host Institution
2.2	Year of publication	Date-yyyy	Publication year of study/paper
2.3	Author	Text	Last name and first initial
2.4	Publication source	List	Choose among publication types
2.5	Article title	Text	

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

Extracted data (Table 3) were 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 process of creating diagrams drew on existing examples outlined in Ackermann & Alexander (2016). 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 to propose diagrams indicating nodes/ variables of interest and the influence between said nodes. 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.

3.3. Results: Systematic Literature Review

A total of 1984 articles were identified during the initial search. After duplicate removal and first stage of screening 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 (**Figure 6**). 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.

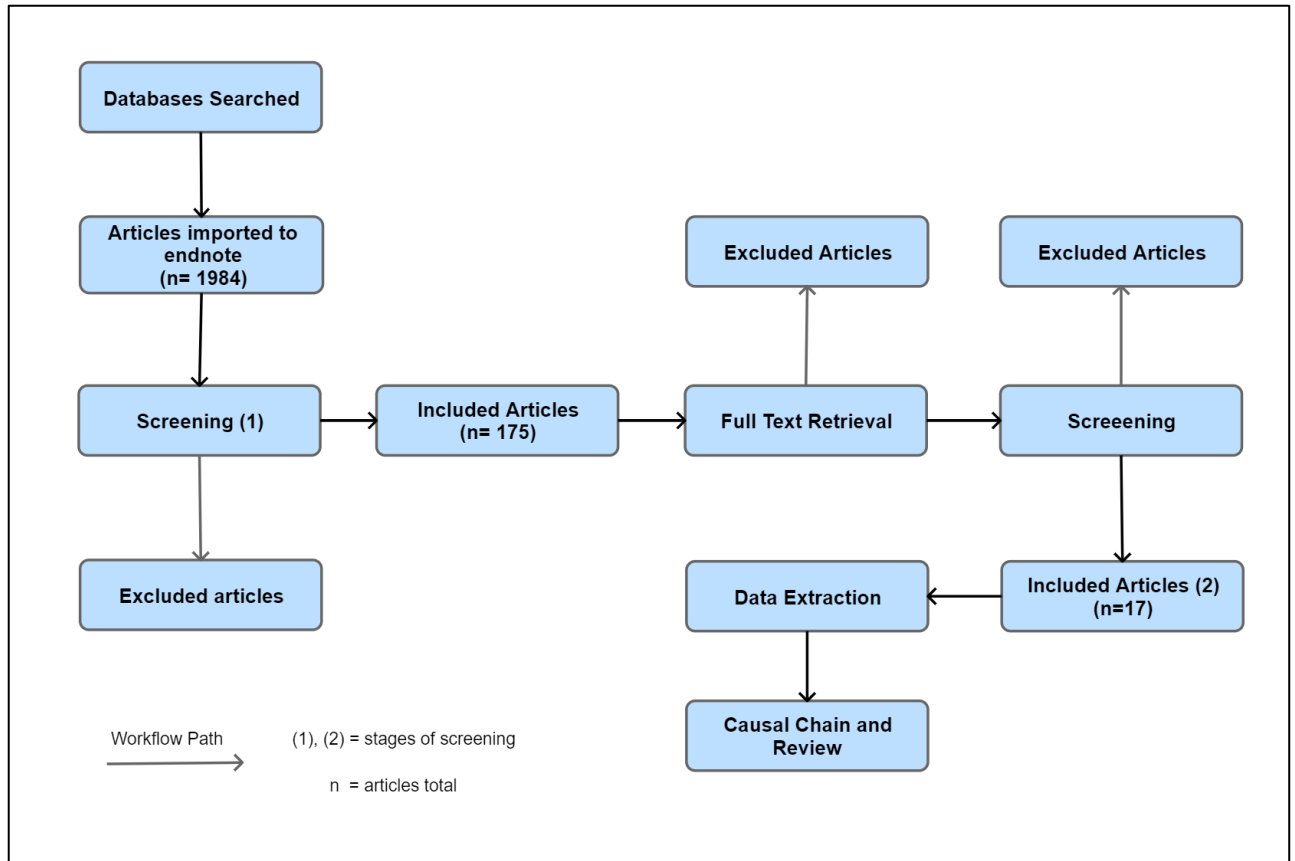


Figure 6- Workflow schematic for the Systematic Literature Review with articles outputted during each stage of the review process.

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 Agryll & 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), Oarweed (*Laminaria digitata*) (Phaeophyceae), Dulse (*Palmaria palmata*) (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.

3.3.1. 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 **Figure 7** and **Figure 8** 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 hybridisation 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/or accidental cultivation of non-native species within an ecosystem or the placement of new artificial and biotic surfaces that facilitates the dispersal of species between disparate habitats (Badis et al., 2019; Miah et al., 2020; Wood et al., 2017).

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 zooplankton, and animal communities such as fish (Benson et al., 2014; Miah et al., 2020; SAMS, 2019; van den Burg et al., 2020a; 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 (Grebe et al., 2019; SAMS, 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 (A. R. 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 (Gegg & Wells, 2019; Miah et al., 2020; SAMS, 2019; van den Burg et al., 2020a).

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* (2018a) observed that the release of volatile gases such as iodine compounds, can lead to cloud formation and changes in local weather.

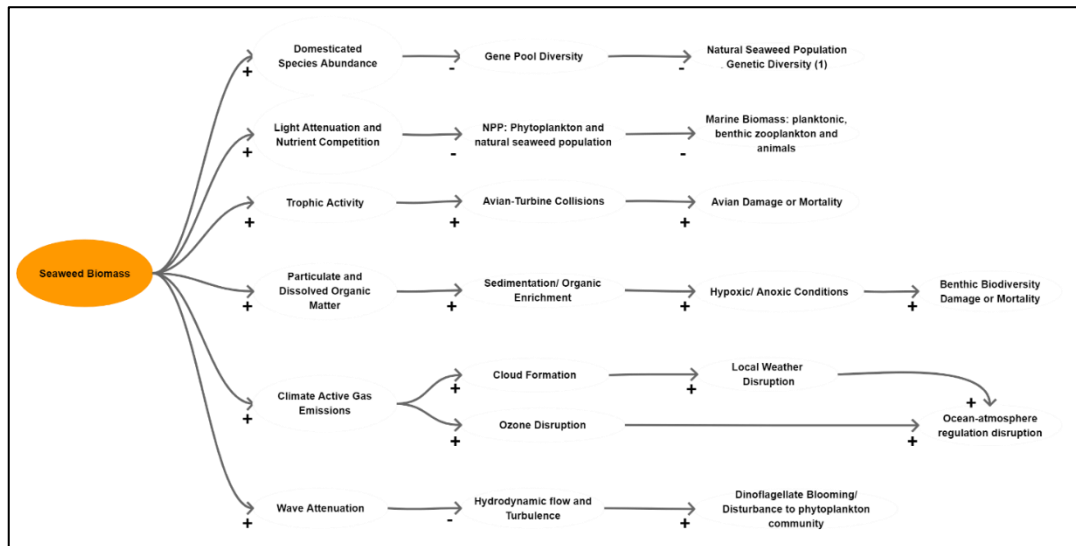


Figure 7- Chain of events leading to negative impacts on environmental systems from seaweed biomass during cultivation inside wind farm array. Sub-impacts (variables) are shown in text with arrows indicating an impact pathway extending from Seaweed Biomass alongside directionality of change (+ for increasing and – for decreasing) for a child node.

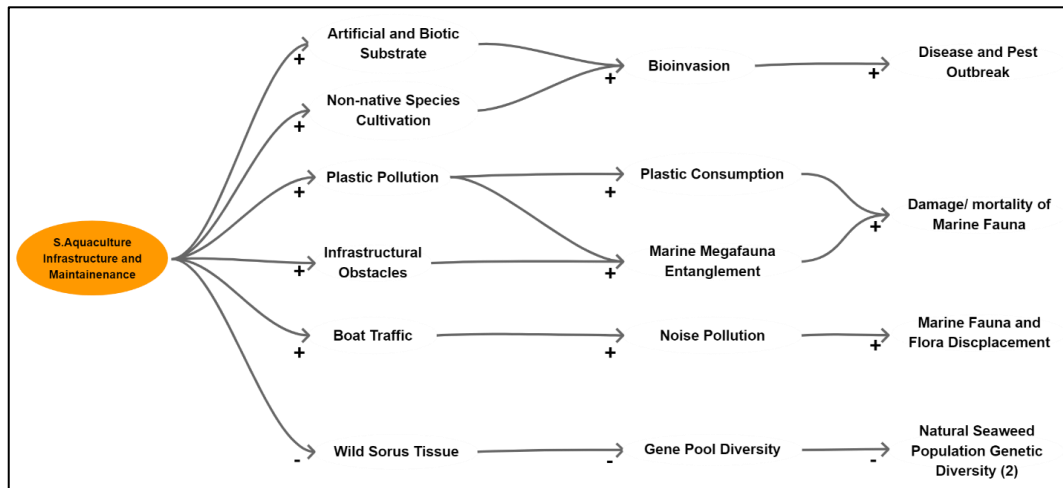


Figure 8- Chain of events leading to negative impacts on environmental systems extending from seaweed aquaculture infrastructure and associated maintenance inside wind farm array. Sub-impacts (variables) are shown in text with arrows indicating an impact pathway extending from Seaweed Biomass alongside directionality of change (+ for increasing and – for decreasing) for a child node.

3.3.2. 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 (**Figure 9**). 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 & 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 nascency 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 (Gegg & Wells, 2019; Gjertsen et al., 2020; Hasselström et al., 2018, 2020; Miah et al., 2020).

Secondly, two impact pathways were considered that resulted from the seaweed cultivar 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 (**Figure 10**) (Clavelle et al., 2019; Pr  at et al., 2018). 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 (**Figure 10**) (van den Burg et al., 2020a).

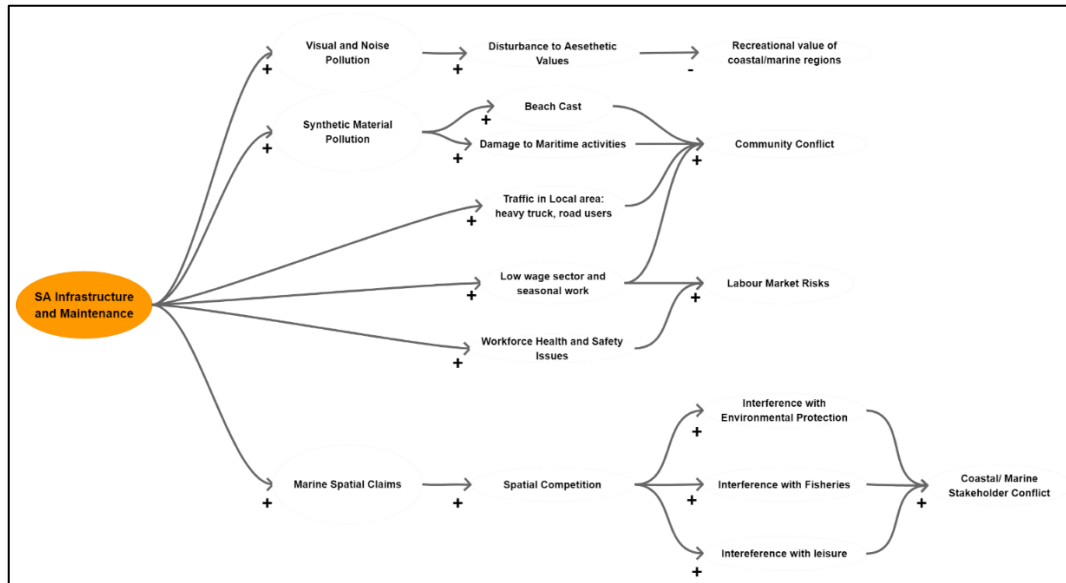


Figure 9- Summary of events leading to negative impacts on social and economic systems extending from Seaweed Aquaculture's infrastructure and maintenance inside Wind Farms. Sub-impacts (variables) are shown in text with arrows indicating an impact pathway extending from Seaweed Biomass alongside directionality of change (+ for increasing and – for decreasing) for a child node.

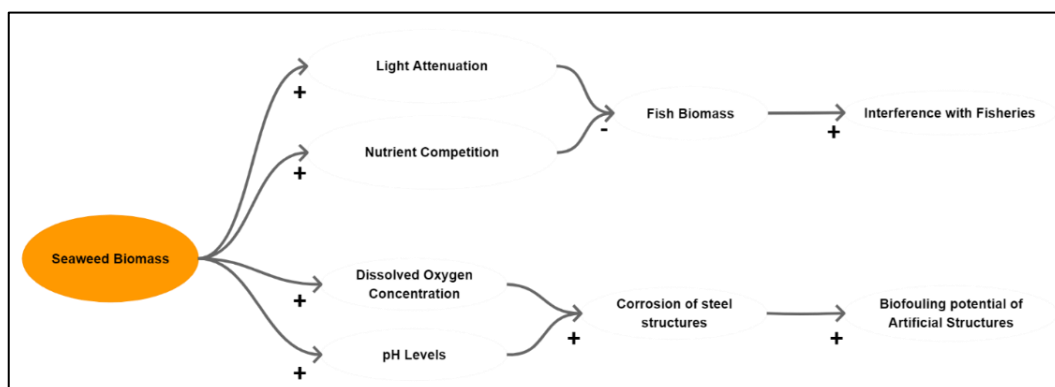


Figure 10- Summary of potential negative consequences extending from the seaweed cultivar inside wind farms. Sub-impacts (variables) are shown in text with arrows indicating an impact pathway extending from Seaweed Biomass alongside directionality of change (+ for increasing and – for decreasing) for a child node.

3.4. 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 (Fig 7-10) 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, depreciating values for cultural and natural heritage and decreasing economic values of community activities (Bracco et al., 2018).

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 proposed as a measure to overcome spatial conflicts with existing marine users, such as fisheries, in the nearshore setting (Abhinav et al., 2020; Buck et al., 2017). 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 (**Figure 10**). 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 (Gawel et al., 2019; Székács, 2017).

My approach illustrated 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 macroalgae-biofuel supply chain (Aitken et al., 2014; Seghetta et al., 2016). 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, therefore, 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 (**Figure 7 & Figure 8**). 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; Miah et al., 2020; SAMS, 2019; van den Burg et al., 2020a; Wood et al., 2017). As a result, this may lead to an overall reduction in the total marine biomass in the system whilst also reducing carbon sink levels-otherwise known as “blue carbon”- of an ecosystem (Benson et al., 2014; Macreadie et al., 2019; Thompson et al., 2017). 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 (**Figure 7 & Figure 8**). 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.

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 use of a cognitive modelling approach to developing the causal diagrams was an attempt to facilitate 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 (**Figure 9**), 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 interdisciplinary collaboration to develop model variables and relationships, prior to undertaking further 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. I 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.

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.

Recent management innovations generated at the interface between Bioeconomy and Sustainability research argue that interdisciplinarity within the modelling and assessment of bioeconomic activity is fundamental 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 multidimensional sustainability within an applied setting of the Bioeconomy transition.

Limitations

The lack of study boundaries created challenges in the accuracy of the review process with significant social and ecological variability being present. 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 with a focus 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. Additionally, bias may be present in results owing to one main reviewer exploring information which limits

opportunities for cross checking and /or confirmation bias with limited perspectives applied to the available evidence. Moreover, full text articles that were not accessible or written in a language other than English would have been excluded and therefore compound bias further to English language institutions and potentially disregard perspectives of those outside English-speaking countries.

3.5. 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 Multi-use 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 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.

Chapter 4

Use of group Conceptual Mapping for Sustainable Development of the MUS: Implications for early-stage innovations.

4.1. Introduction

Understanding the potential consequences across social to ecological dimensions of developing the offshore Multi-use Setting remains a challenge in further implementation of the concept (O'Shea et al., 2022). The use of a Systematic Review for cognitive modelling on the topic provided preliminary understanding including knowledge gaps and complexity, of co-locating Seaweed Aquaculture and Wind Farms. To build on the findings of **Chapter 3**, further techniques are required to handle the complexity found in the situation of developing seaweed aquaculture inside wind farms, including interdisciplinary and collaborative methodologies aimed at resolving knowledge limitations of the MUS scenario (O'Shea et al., 2022). Without adequate, and more accurate, conceptual maps, further analytical techniques including Coupled Component Models (CCM), Bayesian Network (BN), System Dynamics etc., that support management in environmental projects/ contexts will be challenging to deploy correctly (French, 2021; Kelly et al., 2013). Therefore, critical information for realisation and sustainable operational management of the MUS will continue to remain unavailable and withhold the potentially significant socio-economic gains at stake.

The decision to proceed with implementing the MUS has the traits of a complex decision problem (Hemming et al., 2022) with multiple objectives to satisfy (Abhinav et al., 2020), uncertainty of outcomes and risk concerns (O'Shea et al., 2022; van den Burg et al., 2020a). Therefore, the offshore Multi-use Setting will benefit from taking a structured decision-making approach (a process of collaborative, facilitated group-deliberation methods to multiple objective decisions) (Gregory Robin et al., 2012) and integrative assessment modelling techniques - qualitative and quantitative techniques combining social and natural dimensions - (Abhinav et al., 2020; O'Shea et al., 2022). However, to date, few attempts have been made in this direction (Abhinav et al., 2020; O'Shea et al., 2022).

Cognitive modelling, otherwise termed conceptual modelling or mapping, can be used to generate and structure information supporting the decision-making process (Franco &

Montibeller, 2010; Hemming et al., 2022). The resulting structures can promote integrative analytical techniques such as Coupled Component Models (CCM), Bayesian Network (BN), System Dynamics and more, that supports management within environmental projects and contexts (Burgman et al., 2021; French, 2021; Kelly et al., 2013; Luna-Reyes & Andersen, 2003). Cognitive models are a mental representation of a perceived situation by an individual or group (Bol & Hacker, 2012; Eden, 2004; Prezonski et al., 2017). As discussed in Burgman et al (2021), in situations of deep uncertainty and broad impacts, isolated modelling is flawed on the account of inherent cognitive bias individuals have and incomplete understandings of a topic. This fact was prevalent in a systematic review and cognitive modelling exercise of the MUS topic by a single investigator as detailed in **Chapter 3** (O'Shea et al., 2022). Whilst one individual's model may be flawed, eliciting a diversity of models from a larger group can help to overcome silo modelling by capturing the diverse mental models of a situation (Franco & Montibeller, 2010; Burgman et al., 2021).

Group cognitive modelling (GCM) is a technique that provides diagrams for the mental representation of a situation by a selected group of people. It involves a facilitated process to create model frameworks, or conceptual maps, that promote understanding and enable further analyses in decision-making (Burgman et al., 2021). For example, group conceptual models have been used in environmental management to better understand the drivers of forest flammability and risks, showing the value of 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). Group cognitive modelling can be broken into the following stages: 1) convening of experts or relevant parties; 2) an elicitation process whereby conceptual models of individuals on a topic are collected; 3) model aggregation where necessary; and finally, a review of the findings (Cawson et al., 2020; Franco & Montibeller, 2010). The choice of whether to aggregate the models - the process of combining individual model proposals into a shared whole - is a key factor in this approach with options for a facilitator to collect information and propose model(s) or to have subject matter experts co-develop a conceptual model representing a group's consensus perspective (Cawson et al., 2020; Eden, 2004; Franco & Montibeller, 2010). Alternatively, models are not aggregated, and the individual models are explored as a group and by the researcher.

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). Experts - alone or grouped - are recruited and used to make a judgement - qualitative and/or quantitative - on a presented situation, for example, making a prediction for the outcome of an event (Sutherland & Burgman, 2015). However, the use of expert judgement can be susceptible to a host of psychological and contextual problems, leading to inaccurate predictions on a presented topic (Vercammen & Burgman, 2019). Evidence highlights the lack of correlation between an expert's level of, for example, technical knowledge, and their ability to accurately predict an outcome with collective intelligence being, in fact, a stronger indicator of improved performance (Burgman et al., 2011; Vercammen & Burgman, 2019). Although, group size does not have a linear correlation with performance, as Vercammen and Burgman (2019) conclude, the maximal gain in terms of accuracy or "value for money" tends to be a group of around 10 to 15 individuals. In addition to considerations of group size, the diversity of the group also improves performance of prediction in the expert elicitation process. The reason is group diversity, defined as variation in "age, gender, cultural background, life experience, education and specialisation" (Hemming, Burgman, et al., 2018, p. 175), is shown to be an indicator of intellectual diversity and will result in different mental models and thus improve the judgement process (Page, 2008).

Moreover, further improvements to the expert elicitation process using a group can be made when using a structured methodology over unstructured methodology whereby stages or questions to elicitation process are not well-defined (Burgman et al., 2011). A well-used method for structured group elicitation is the Delphi method. The Delphi method was invented by the RAND corporation (Dalkey & 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). Application of the Delphi method typically follows three steps: expert selection and recruitment, elicitation via survey, and/or interviews, with opportunities for feedback and discussion (Mukherjee et al., 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).

Without further understanding of the potential consequences across social and ecological dimensions of developing an offshore 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 Chapter, I present a hypothetical case study for the Multi-use Setting to provide system boundaries for assessing a Multi-use Setting system and explore this case-study using group cognitive modelling technique and evidence synthesis to identify and characterise the potential consequences across social, economic, and environmental objectives.

4.2. Methodology

4.2.1. Hypothetical Multi-use Setting Case Study

As there were no available real-world case studies, a hypothetical scenario was developed to establish a context for performing cognitive modelling of the co-located MUS topic – allowing me to define social and ecological variables and spatial and temporal system boundaries as required for the assessment (Hodgson et al., 2019). The hypothetical scenario was created using a quick scoping literature review of peer and non-peer reviewed sources using a keyword search primarily of “offshore seaweed aquaculture”, “offshore wind farms” in Scopus and Web of Science Imperial College London’s subscriptions in addition to input from project stakeholders. Seaweed aquaculture was selected on account of technical feasibility and strong industrial policy support evidenced by the latest EU Algae Strategy (European Commission, 2022); and coalition networks such as EU4Algae (European Commission, n.d.), Algae UK (Algae-UK, n.d.) and Safe Seaweed Coalition (Seaweed Coalition Global, n.d.).

Support for the idea of offshore aquaculture has resulted in several developments on offshore aquaculture feasibility including infrastructure, operating protocols and regulations (Buck et al., 2017; Froehlich et al., 2017; NOAA, 2016). Despite interest in offshore aquaculture, costs of production are high and stakeholder opposition is still a concern (Buck et al., 2018; Holmer Marianne, 2010). Combining wind farms and aquaculture in a MUS provides a potential pathway to address some of the implementation issues facing offshore aquaculture. Suggested

key 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). Co-location for combining aquaculture farms involving extractive species and wind farms have been considered but not yet actualised as standard operations (Buck et al., 2017). Extractive species include bivalves (filter-feeding molluscs found extensively in different aquatic environments) (Canesi & Pruzzo, 2016) and seaweed, also known as macroalgae, (photosynthetic organisms found in marine ecosystems) (García-Poza et al., 2020). Operationalising the Multi-use Setting concept in the initial stages, using extractive species, particularly seaweed, may be pragmatic for multiple reasons. Firstly, seaweed aquaculture is considered to have lower levels of environmental impacts during cultivation (Visch et al., 2020) and trials of seaweed aquaculture in the North Sea have demonstrated infrastructure that is deployable in the offshore environment (Buck et al., 2017; Buck & Buchholz, 2004; Grandorf Bak et al., 2020). Furthermore, protocols are available for transferring brown seaweed species aquaculture to offshore conditions (Buck et al., 2018). Lastly, expanding 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). Thus, the hypothetical case-study was built on the principle of seaweed farming in conjunction with wind-farming.

The North Sea territory formed the basis of the hypothetical case study. 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 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., 2017b) and it has one of the largest commissioned wind farms sited in the area; namely, Hornsea Project One (Ørsted, 2020). The Hornsea Project 1 is the first stage of four total developments that are being constructed and was commissioned for operation in 2020 (Ørsted, 2020). The site location is approximately 65km off the coast of the Yorkshire County and consists of 174 fixed turbines that are dispersed across a total area of 407.30 km² (Ørsted, 2020).

Table 4 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 (HWF) 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 (869.19km²) and increasing in size over the next ten years to reach 100% of the wind farm boundary.

Table 4- 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 (km²)	Total Area (km²)
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	

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., 2017b). Based on experimental studies of three aquaculture designs, a 5-metre diameter ring shaped rig device, comprising of an anchor point, metallic components, 80-100 metres 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 figure 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 Grandorf Bak *et al* (2020, p 346) as a “sheet-like structure with free moving cables and single mooring” with “flexible hybrid long-line 6.5 metres long and 5 metres deep”- see figure 2 of Grandorf *et al* (2020) for referenced imagery. The installations provided were illustrations of potential structures participants could use to assist with visualising and investigating the hypothetical scenario.

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 (**Figure 11**).

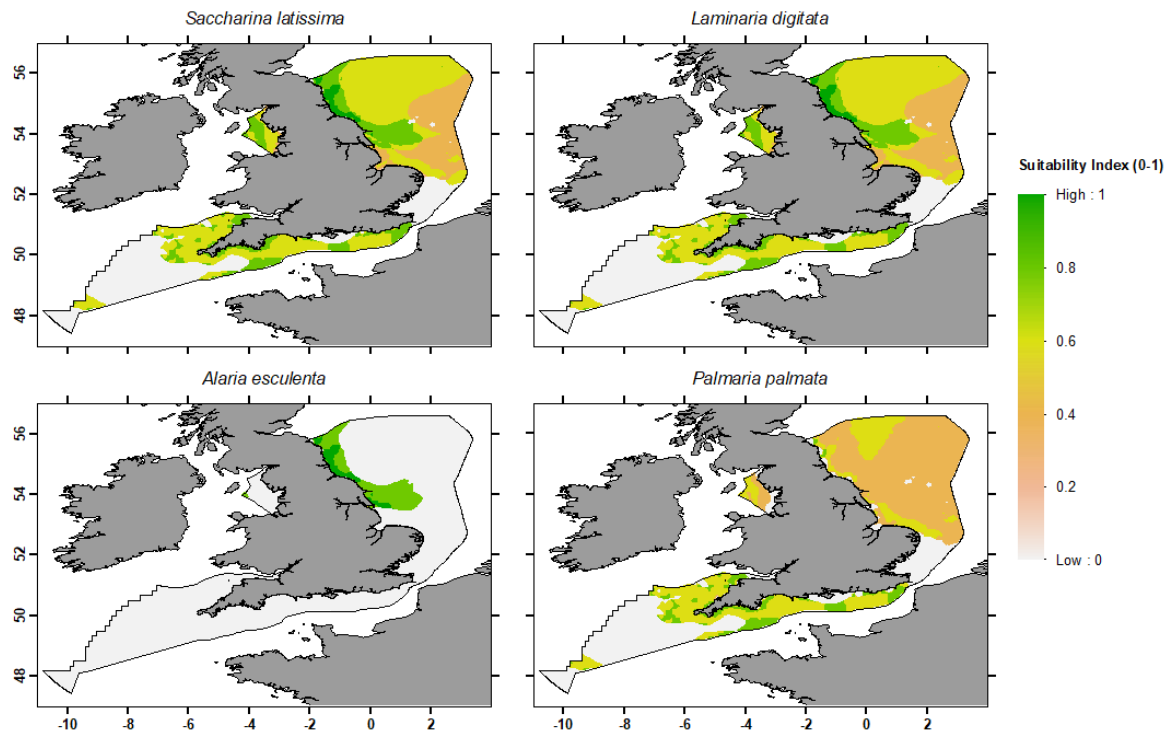


Figure 11- Maps showing suitability of farming seaweed species *Saccharina latissima*, *Laminaria digitata*, *Alaria esculenta* and *Palmaria palmata* in the territorial waters of the UK - figure extracted directly, with no edits from MMO (2019).

Similarly, the report by Buck et al (2017b) suggests seaweed species potentially best suited to offshore conditions in the European case studies generally derived from the *Laminarian* genus, such as *Saccharina latissima* and *Laminaria digitata*, however, other species from different genus are also disclosed in the report but less often. The species cultivated during the hypothetical scenario are Sugar Kelp (*Saccharina latissima*) and Oarweed (*Laminaria digitata*). Biomass density of the farm had been excluded due to data and resource limitations. Thus, these species were considered in our hypothetical case-study.

4.2.2. 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 development of a MUS integrating seaweed aquaculture with a wind farm (**Figure 12**). The group cognitive modelling (GCM) process was performed using a modified Delphi method

following the guidelines outlined in Okoli & 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 (SME) 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 impacts of the hypothetical scenario proposed for this assessment. The elicitation process ended by April 2022.

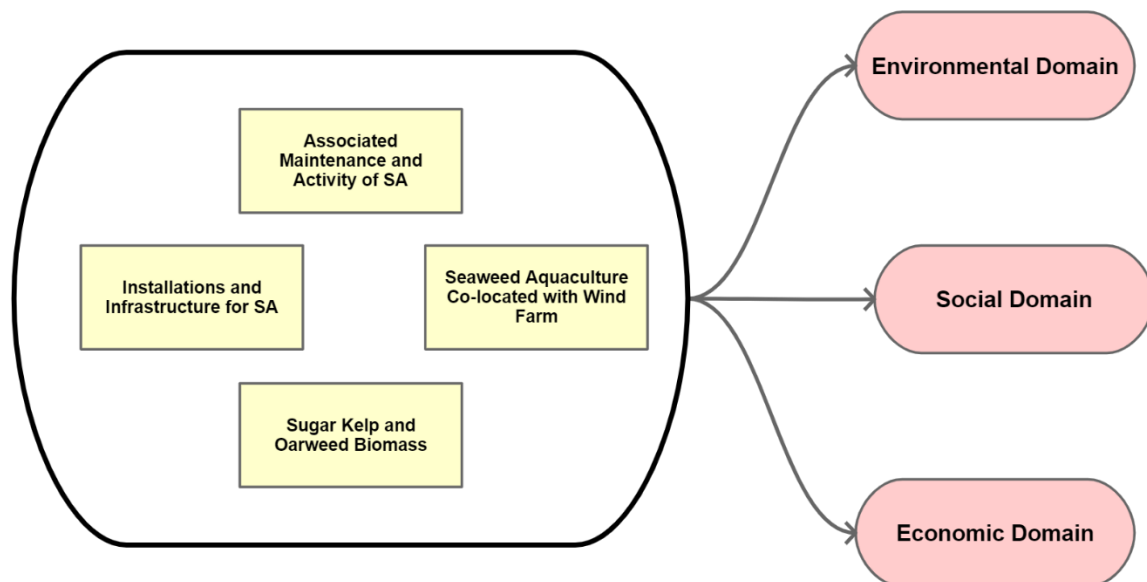


Figure 12- Summary schematic outlining the concepts that are the focus of the Delphi panel interviews (Yellow boxes) and the direction of influence extending from said concepts being explored by the panel against environmental, social and economic objectives. SA = seaweed aquaculture

4.2.2.1. Participant recruitment and group organisation

Subject matter experts (SMEx) 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 & Pawlowski (2004) to help guide the recruitment process. 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 natural or social domains. The target size of the total group was between 10 and 20 participants as recommended by Hemming et al (2018), with the final group containing 13 individuals roughly split between social and natural domains. SMEx 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 Multi-use Setting system were first defined (Table 5) and then used to search and evaluate potential SMEx for recruitment.

Table 5- Relevant knowledge criterion used to guide the search, evaluation and recruitment of subject matter experts relevant to the social, technology and natural dimensions 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	-Academic -Executive agency of government -non-governmental organisation/ Charity -Industry/ Business
	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	
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 natural) was created alongside their contact details. Ethical approval was received 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 (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., 2018; 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).

4.2.2.2. Individual Cognitive Model Development

Individual consultation via telecommunication including email and Microsoft Teams was conducted starting in September 2021 and lasting up to an average of 1.5 hours 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 (Table 6). Subject matter experts were given

time to investigate the topic and provide responses to the questions via a survey sheet akin to a horizon scan (Sutherland & Woodroof, 2009).

Table 6- Survey questions for participants

Survey Questions

- 1) *Please list the consequences (positive and/or negative) you believe the scenario will have on biodiversity.*

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.*

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 societal community members and networks.*

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.

- 4) *Please list the consequences (positive and/or negative) you believe the scenario will have on marine resources used by relevant stakeholders.*

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.

5) Please list the consequences (positive and/or negative) you believe the scenario will have on economic development.

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 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. The structured format was then used 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 RO 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 reflected their perspective on the hypothetical scenario and questions (Table 6). 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.

4.2.2.3. Shared Cognitive Model Development

After all 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 adapted from the description of facilitated modelling techniques common to operations research using telecommunications – this was for communicating with participants owing to the UK Coronavirus restrictions (Burgman et al., 2021; Franco and Montibeller, 2010). 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 by the group, based on emergent properties of individual maps, whereby a predominantly social, economic, or environmental theme of the effects is concluded (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 effecting social communities (social domain), economic activity (economic domain) and/or natural ecosystems (environmental domain) (**Figure 13**).

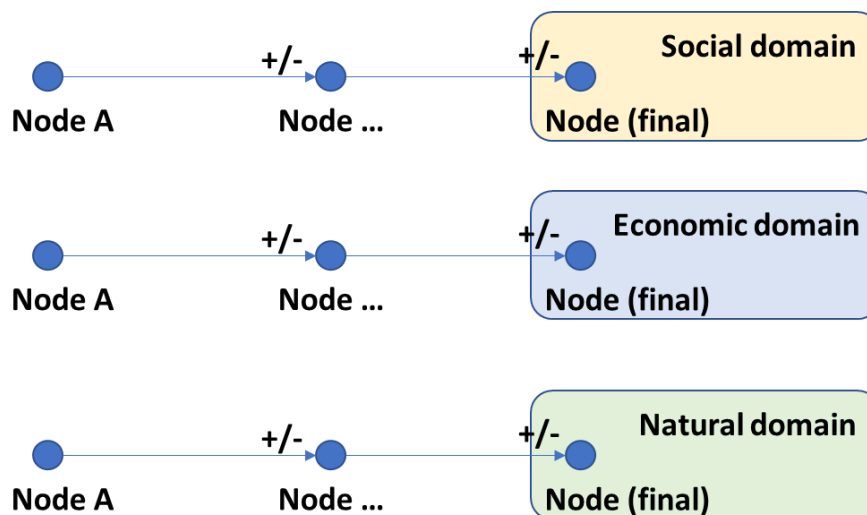


Figure 13- Schematic illustrating the process of categorising impacts into themes based on the domain of the final impact/ nodal change e.g. largely effecting marine wildlife, wind farm infrastructure and so on.

The impact tables were then used to integrate the cognitive maps to develop a shared cognitive model of the 13 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?”

“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/or interference with the experts’ beliefs owing to the subjective interpretation of the findings by the facilitator (Ryan O’Shea). 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 variables 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 facilitator and SMEx in addition to Microsoft Teams lasting up to 60 minutes of call time, between the months of April 2022 and ending in April 2023.

4.3. Results

4.3.1. Group Cognitive Modelling

A panel of 13 subject matter experts were convened which resulted in 29 individual cognitive models. Separate models were proposed by an individual SMEx based on the objectives of interest including environmental, social and economic. The 29 individual models were integrated into five shared cognitive models by me and accepted by the SMEx panel explaining the perceived consequences of establishing the hypothetical scenario for seaweed farming in an MUS at Hornsea across economic, social and environmental objectives. Impact tables were produced providing a list of the suggested consequence alongside an explanations for their causality. Impacts were categorised by objectives -environmental, economic and societal - and sub-themes within each objective considered emergent themes of the assessment.

4.3.2. Social to Ecological consequences

The “Abiotic map”, collates all the perceived final impacts to the non-living components of the ecological system (Figure 14). 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 changes 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 seaweed aquaculture industry development and disruptions to the operations of the offshore wind farm (**Figure 14**). Moreover, the abiotic model included trade-off events. For example, 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 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 (**Figure 15**). 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 (**Figure 15**).

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 area resulting from the introduction of seaweed aquaculture into the wind farm array (**Figure 16**). 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 value added extraction and new biomass production and microeconomy activity in the area.

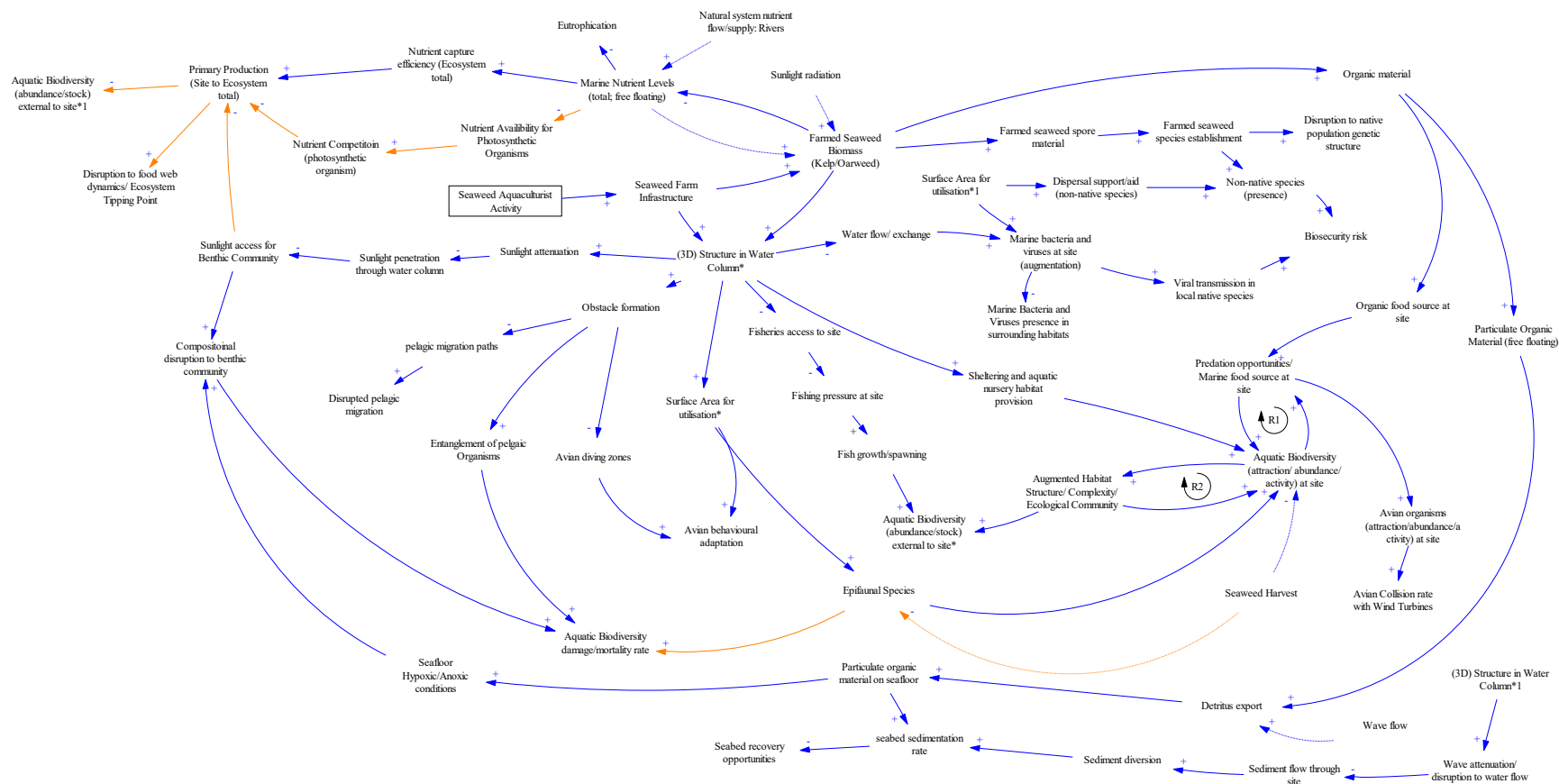


Figure 15- Standardised and shared cognitive model on the potential impacts to environmental (biotic) system of the hypothetical scenario of expanding seaweed aquaculture inside Hornsea Wind Farm over the next ten years. - Arrows show the conditional probability between variables identified (blue for primary and orange for additional/ secondary pathways); 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 (variable(s) extending from prior impact/ parent node).

The “marine economic stakeholders” map details the perceived consequences to stakeholders from utilising oceanic resources for commercial purposes (**Figure 17**). Multiple existing stakeholders were perceived to be affected by the seaweed aquaculture development including the 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 (**Figure 18**). 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 (**Figure 18**). 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.

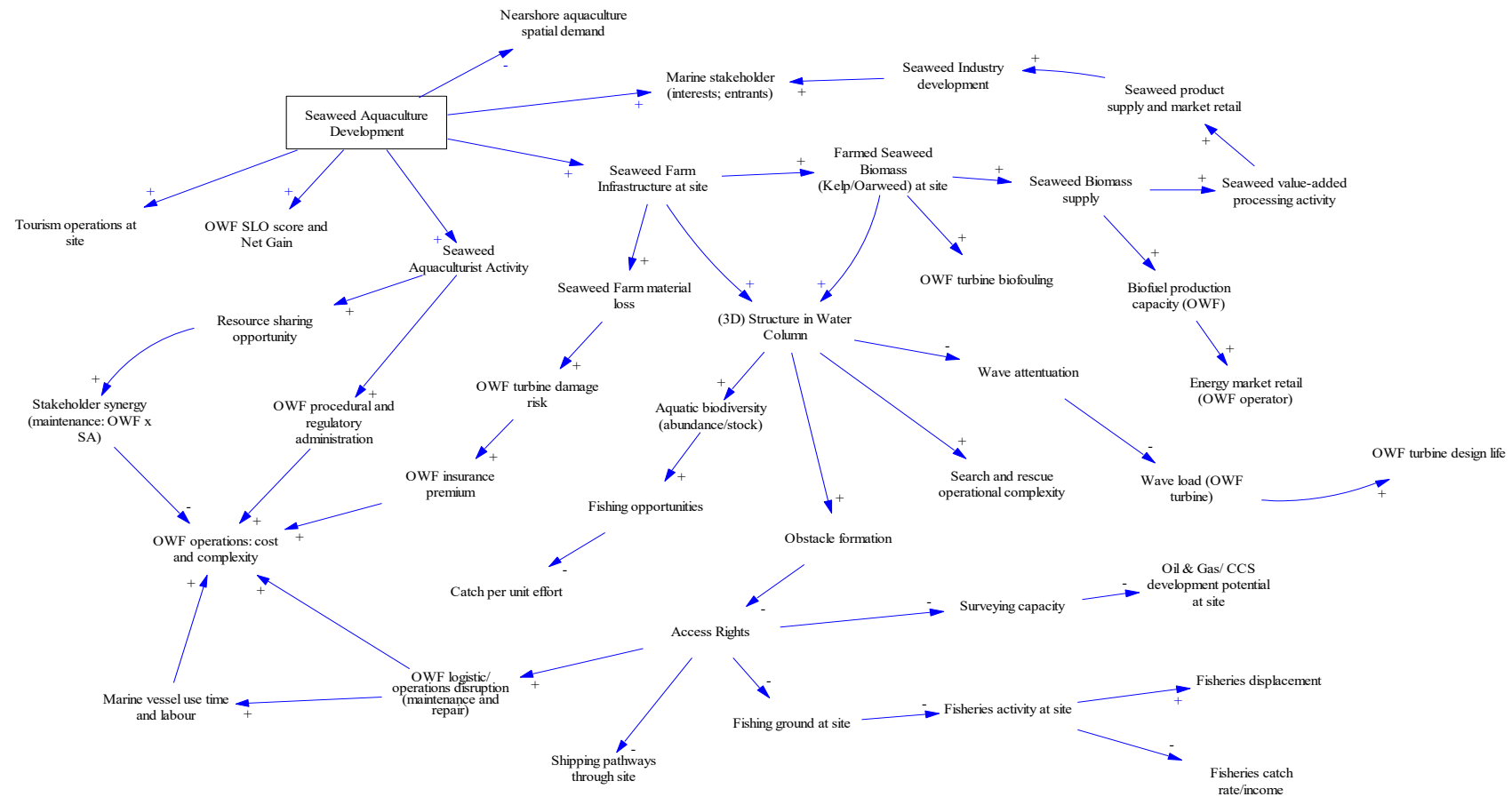


Figure 17- Standardised and shared cognitive model on the potential impacts to social system (Marine Economic Stakeholders) of the hypothetical scenario of expanding seaweed aquaculture inside Hornsea Wind Farm over the next ten years. - Arrows show the conditional probability between variables identified (blue for primary and orange for additional/ secondary pathways); 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 (variable(s) extending from prior impact/ parent node).

The cognitive maps in addition to iterative surveying were also used to produce a catalogue of the suggested impacts with descriptions of the cause(s) - see supplementary materials (“impact tables (standardised)”). The impacts tables also included evidence sources relating to the impact and the SMEx(s) who identified the proposed variables, A condensed summary of the impact table is found below (Table 7).

Table 7- 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.

<u>Objective</u>	<u>Entity</u>	<u>Suggested Impact</u>	<u>Number of identifiers</u>
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 Alkalisiation	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
	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 (Carbon 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

4.3.2.1. 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 panellists, with opportunities to supply evidence to support their claim. Table 8 captures commentary of panel members contesting specific claims with the likelihood of five impacts being contested/ disagreed on by the panel members. The main impacts proposed in which their likelihood or accuracy were 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; reduction in livestock emissions from consumption of seaweed- based products; resource sharing opportunities with bioenergy product potentials and reduced operational costs for OWF; improvements to human and livestock health and; increased economic circularity capacity and activity.

Table 8- 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 <i>Asparagopsis taxiformis</i> by McConnell and Fenical (1977) and benefits and risks of including the bromoform containing seaweed <i>Asparagopsis taxiformis</i> 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
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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)
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Economic circularity capacity and activity	Claim contested by an individual SMEx panel member	“More waste doesn’t inherently lead to more circularity in the economy if infrastructure or capacity for recycling isn’t available in first instance”	Not supplied
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4.4. Discussion

Overcoming the implementation gap of the Multi-use Setting requires improved understanding of the consequences of MUS development across social and environmental dimensions to facilitate a more integrated management approach (Abhinav et al., 2020; van den Burg et al., 2020b). The use of a hypothetical scenario and Delphi methodology initiated a structured decision-making approach (Hemming et al., 2022) to the seaweed aquaculture-wind farm system with the aim of enabling further integrative analyses and management of implementation in real-life systems. The information sourced elucidates the potential consequences perceived from developing seaweed aquaculture inside an existing wind farm. The cognitive maps and impact tables illustrate the complexity of advancing the MUS concept, with various factors that should be considered in the management of developing a seaweed aquaculture-wind farm system. Moreover, the methodology has broader implications for the Circular Bioeconomy transition demonstrating a novel integrative assessment approach, required for biosystem developments providing an entry point to enable further integrative assessment and modelling techniques (French, 2021; Kelly et al., 2013; Wohlfahrt et al., 2019).

Consequences of the Multi-use Setting

An emergent theme of the assessment were 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 global warming potential depending on the carbon budget of the supply chain with knock on effects to existing wind farm maintenance operations. The system may promote and/or damage biodiversity because of providing habitat functions that supports marine life or cascading effects that threatens populations levels. The system could raise income and/or cause debt

depending on how the projects are implemented; 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 and if progressed, during the implementation and scale up of production systems. It cannot be assumed that the outcomes of a MUS project are solely positive or negative and outcomes may be mixed within, and across, the sub-objectives of sustainability- social, economic, and environmental. Having identified potential impacts, these 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).

Despite the major socio-economic advantages of pursuing an MUS-type system being claimed; namely, minimising marine stakeholder conflicts (Abhinav et al., 2020; Przedzimirska et al., 2021), the cognitive mapping provides contradictions for 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 (**Figure 17**).

Furthermore, the carbon sequestration potential of seaweed aquaculture as a tool to mitigate climate change is repeatedly advocated (Alleway, 2023; Duarte et al., 2022). However, this presents an incomplete picture of what may happen, with the carbon budget of seaweed bioeconomic projects based on the supply chain dynamics (context-dependent) and the complexity of carbon flux in social-ecological systems- increasing or decreasing through several direct and indirect pathways (**Figure 14**). This highlights a broader management criterion for the MUS that the scale of the project cannot be understated or simplified. A systemic overview including diverse expertise and methods across natural, engineering, and social fields, to understand outcomes is always needed in each MUS context to effectively meet the multiple objectives criteria set out by sustainability frameworks such as the United Nations' Sustainable Development Goals. In doing so, would make the innovation process surrounding the MUS more holistic and align with sustainable innovation development as opposed to becoming purely techno-economic, social or environmental (Silvestre & Țîrcă, 2019).

On the other hand, 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 products (Padam & Chye, 2020), and this was reflected during the cognitive mapping process (see supplementary materials, “impact tables (standardised)”). As a consequence, owing to the variety of product outcomes, this could 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 (**Figure 16**).

Even within this study, claims by experts were counter-claimed with evidence on the probability of an outcome to result (Table 8). Given the multiple scales of seaweed aquaculture that was 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 (Hodgson et al., 2019). 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. Therefore, thorough monitoring is recommended in initial pilots to generate data and information that can help to further alleviate the uncertainty of impacts we have identified in our assessment that were previously unknown. The development of seaweed aquaculture and wind farms occurs in a dynamic, open ocean environment and connected social network of actors and infrastructure that makes prediction, particularly of risks, extremely difficult due to the complexity of the environment and state of flux (Duffy et al., 2014; Refulio-Coronado et al., 2021). Nonetheless, adequate monitoring of key social, economic, and environmental indicators will help to reduce or work with uncertainty and support adaptive management with growing body of relevant information for management of the MUS.

Multi-use Setting in the Bioeconomy and role of Decision Analysis

The multidimensional nature of sustainability creates complexity within the decision-making process owing to the need to synergistically meet multiple objectives and thus limit trade-offs across social, economic, and ecological dimensions (Bakshi, 2019; Urmetzer et al., 2020; Wohlfahrt et al., 2019). Innovations are often criticised within the Sustainable Bioeconomy transition as lacking the integrative perspective in technology and process developments leading to inadequate means to identify the detrimental effects across spatial and temporal gradients within broader social and environmental dimensions (Gawel et al., 2019; Schutter et al., 2019). On the other hand, structured decision-making and the related techniques have been

attributed to finding “win-win” solutions to the management of environmental systems (Gregory Robin et al., 2012). Introducing cognitive mapping early in the innovation cycle as performed in our study provides a novel approach to implementation by accounting for the multidimensional nature of management early in the assessment phase of technology and complex biosystem proposal. This approach provides sufficient time to devise alternative strategies, recognise trade-offs and the risk potentials that would otherwise not be known until implementation where reversal of a decision may be infeasible or costly.

To elucidate, the use of cognitive mapping falls within the methodologies attributed to Decision Analysis and would typically contain five stages prior to a decision of implementation including problem definition, evaluation and developing alternative decision choices (Hemming et al., 2022). However, alternative decisions were not considered during this assessment and should be followed up given the uncertainties and potential trade-offs of developing seaweed aquaculture inside Hornsea Wind Farm. For example, integrating seaweed aquaculture inside the wind farm array was opined to have negative implications to existing economic activity such as causing a loss in income for other marine stakeholders. Furthermore, the seaweed aquaculture itself may be economically unfeasible leading to debt and instability (**Figure 16**) (van den Burg et al., 2016).

Based on the uncertainty and rather than risk debt, switching focus to developing nearshore seaweed aquaculture and biorefinery pilots in conjunction with strategies for future scale-up of production inside a wind farm is one type of alternative decision. Use of nearshore pilots may then catalyse a “learn-by-doing effect” that is useful in the innovation cycle for maturing activity and processes and provides information for decision-making (Hellsmark et al., 2016; IPCC, 2022), and presently lacking in the offshore MUS context such as economic data (van den Burg et al., 2016). To that end, process systems engineering techniques can be used 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). However, alternatives should be considered more rigorously and understanding potential implications of alternative decisions against the implementation of seaweed aquaculture-wind farm systems (Hemming et al., 2022).

The Multi-use Setting is a complex project to implement, needing to satisfying multiple objectives concurrently. Nonetheless, methods and decision support tools are available in the

realisation of MUS systems that could lead to tangible benefits, but managers should exercise caution and robustly consider all risks that come with the project, social and ecological. Further research should continue with the structured decision-making process in the MUS, especially, evaluating probability (likelihood and severity) of outcomes within and across the objectives using further integrative assessment and modelling techniques such as Bayesian Network or Bioeconomic modelling (Kelly et al., 2013). More broadly, this study has demonstrated an integrative method that can be applied to bio-based innovations struggling with the multidimensional criteria of sustainability objective and will be useful to convene groups and knowledge to work with the uncertainty in progression of proposals locked at the conceptual phase.

Limitations

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). Although, the approach provided a high-level snapshot of potential consequences, the methodology has limitations given the resource constraints and availability of participants. 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. I also aimed to include a diversity of perspectives in the subject matter expert panel in attempt to limit bias, however, greater diversity in the representation of the panel should be sought given the known benefits of this criteria in prediction performance (Hemming, Walshe, et al., 2018; Page, 2008). For example, the high-level investigation should be counterbalanced with inclusion of local relevant parties affected by proposed development plans/ projects in future research (Keen, 1997). The cognitive modelling process also 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 predictions (Burgman et al., 2021; Hemming, Walshe, et al., 2018).

4.5. Conclusion

The use of a Delphi and cognitive mapping methodology generated information regarding the perceived social and ecological consequences of developing seaweed aquaculture over the next ten years inside Hornsea Wind Farm array. Impacts expressed by the group of subject matter experts were diverse carrying positive and negative implications across social, economic and environmental objectives. The cognitive maps illustrate the complexity of implementing MUS projects whilst satisfying multiple objectives and contradicts the claims about the MUS namely, that they reduce stakeholder conflicts, and the carbon sequestration potential of seaweed. This, traditional claims about MUS often disregard the nuances for the severity or likelihood of impacts on stakeholders and climate.

The methodology provides a novel integrative assessment of an MUS-type system and provides structured information to support innovation management including trade-off identification and further methodological applications required to reduce uncertainty in decision-making. Uncertainty remains about the probability of effects extending from seaweed aquaculture development inside the wind farm and thus, further decision analysis and integrative assessment modelling techniques would be valuable to support management. More broadly, the use of Delphi and cognitive mapping was a valuable contribution in assessing the multidimensional nature of early phase innovations in the Sustainable Bioeconomy transition. Providing a means to account for multiple objectives and foresee costly decisions that may be an oversight during technology and complex process systems development. Having obtained and structured information from relevant parties about the MUS situation, further management techniques including modelling, can now be deployed to improve understanding and prediction of outcomes of the innovation for sustainable operational management.

Chapter 5

Environmental Sustainability Trade-offs and Risks of Co-locating Seaweed Aquaculture and Wind Farms

5.1. Introduction

The integrative assessment performed in **Chapter 4** revealed the perceived effects resulting from a hypothetical scenario of seaweed aquaculture development inside of Hornsea wind farm. However, uncertainty remained about consequences including probabilities and the sustainability implications of progressing with implementation (**Chapter 4.1**). Having elucidated potential impacts, minimising, or mitigating the trade-off and risks is a critical step to securing community support to proceed with projects, especially, for meeting the sustainability objective as prescribed by Circular Bioeconomy and Blue Economy strategies (van den Burg et al., 2020a; van den Burg et al., 2020b; European Commission, 2020; Gawel et al., 2019; Hausknost et al., 2017). Therefore, this chapter aimed to explore the environmental sustainability trade-offs and potential risks of scaling-up seaweed production inside the Hornsea Wind Farm over the next ten years.

5.1.1. Decision Analysis in the MUS: trade-offs and risks

Structured Decision-Making (SDM) also commonly known as Decision Analysis, is a proven procedure that accounts for the complexity in environmental decision-making including consideration of trade-offs and risks, to improve outcomes of management (Hemming et al., 2022). The process of SDM attempts to resolve the difficulties of complex environmental decision-making such as managing uncertainties and/or trade-offs between a multi-objective criterion and is attributed to sourcing “win-win” scenarios for social-ecological system interactions i.e. maintaining/ promoting ecological functionality concomitantly with social advancements (Gregory Robin et al., 2012). Decision Analysis is broken into seven, iterative stages ranging from defining the problem to evaluating the outcomes of a decision before making a choice (Hemming et al., 2022) (**Figure 19**). Central to SDM is that decision choices are not bounded to one option but assessed in comparison with a portfolio of choices, aiming to maximising the beneficial outcomes. At each stage of the SDM process, information revealed can be used to support management and the prior stages in the decision-making

process. For example, as risks are elucidated about a decision, one may revert back to alternative choices and reconsider the available options (Hemming et al., 2022). **Chapter 4** estimated the consequences of developing seaweed aquaculture inside a wind farm, thereby completing step 4 of the DA process, as a result the next step is to identify and evaluate trade-offs (step 5) to enable decision optimisation to follow (**Figure 19**).

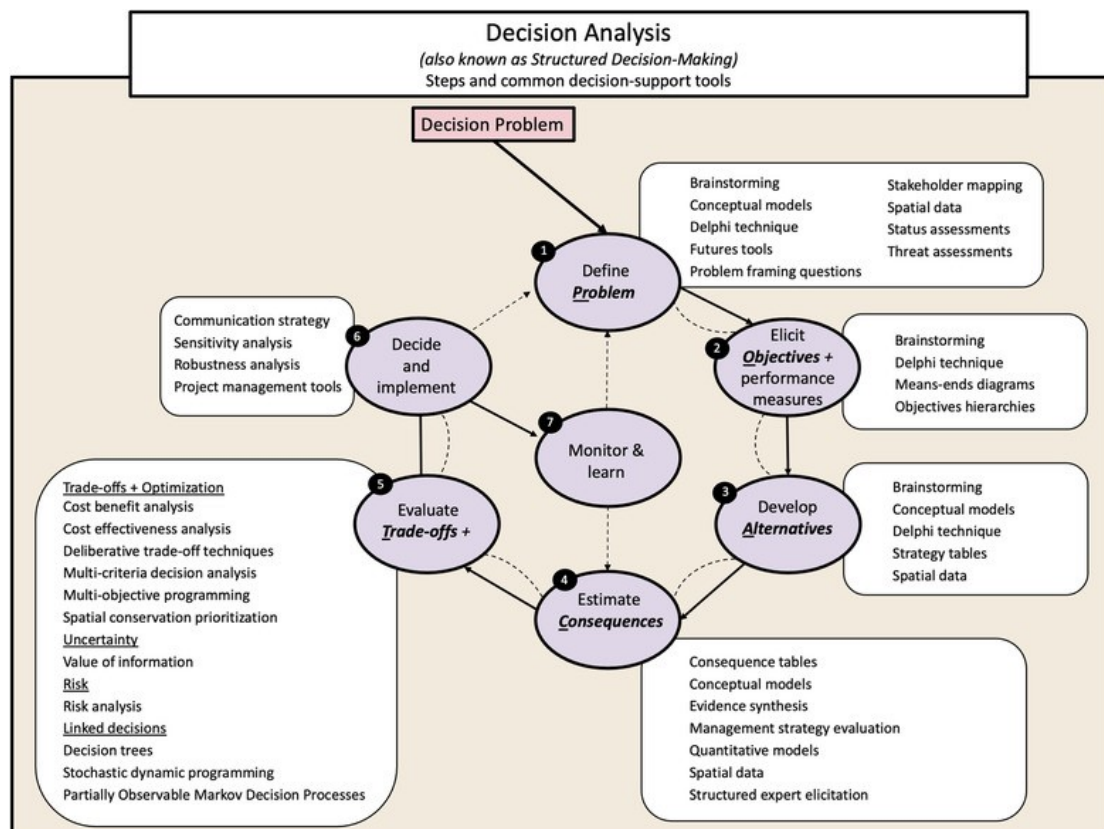


Figure 19- Outline of the Decision Analysis process including key stages and related techniques for resolving different challenges in the decision-making process of complex (environmental) problems (Hemming et al., 2022). For the MUS, stages 1-3 were established in the background section (**Chapters 2.1; 2.3; 2.3.1**) based on previous studies; stages 3-4 of the Decision Analysis process for the MUS were completed in **Chapters 3** (O’Shea et al., 2022) and **4**.

Trade-offs in decision-making may occur in multiple forms including a loss in one objective such as economic, at the expense of securing another such as environmental (Hemming et al., 2022). The proposed benefits of considering trade-offs in environmental management is it can lead to sourcing better alternative decisions choices and/or provide decision-support tools and

frameworks (Hemming et al., 2022; Morrison-Saunders & Pope, 2013). A holistic approach to conceptualising trade-offs in evaluations is the use of “trade-off rules” proposed by Bob Gibson (2012). A basic assessment criteria for these trade-off rules are shown in **Figure 20**.

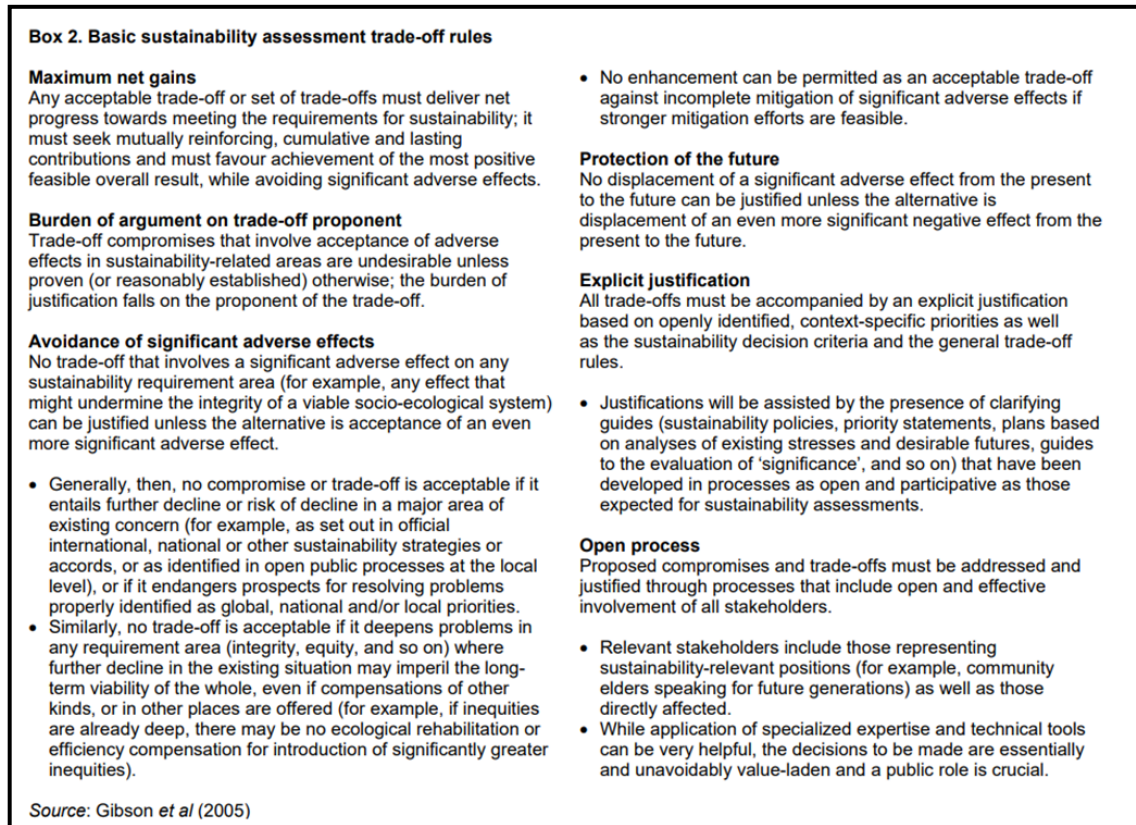


Figure 20- Basic trade-off rules proposed in Bob Gibson (2013) for sustainability assessment of project development- figure extracted directly, with no edits from Gibson (2013).

The trade-off rules system proposed by Gibson (2012) is formed from requirements/ statements – set by the manager and/or group of relevant parties- to evaluate a project and any outcomes that do not meet these requirements would then be identified as a trade-off in the decision-making process. Furthermore, depending on its significance, the outcome may invalidate the sustainability claim of a proposal and infer a risk. The term “risk” in this case refers to the uncertainty including likelihood of a negative consequence extending from an activity against a defined objective/ human value such as preventing biodiversity loss, minimising hazards at work and so on (Hauschild et al., 2022; Hodgson et al., 2019). Risk assessment is a closely related but an additional process that investigates the outcome(s) of an activity and evaluates the activity with regards to the uncertainty and threat posed to an objective from a project

impact. Risk analysis typically follows a procedure of defining the subject and units of study, identifying drivers of risks followed by evaluations to characterise the nature of a risk (Hodgson et al., 2019). Advancements in risk analysis have also focussed on the risk management process itself. This includes recognising and making consideration of the subjective nature of risk evaluations and the cognitive issues that affect the validity of results including cognitive bias (Hodgson et al., 2019). Furthermore, there is also a need for greater integrative procedures drawing from theory across social and natural sciences to overcome limitations in standardised procedures based on single disciplines (Hodgson et al., 2019).

5.1.2. Sustainability objective

To advance an assessment of trade-offs and risks in the decision-making of the MUS, objectives are required as part of the process to define negative (or positive) outcomes (Hauschild et al., 2022). As the MUS is an innovation that can be considered within the Blue Economy and Circular Bioeconomy thus it can be assumed social-ecological sustainability is the overall management objective (Bell et al., 2018; Heimann, 2019; Przedzimirska et al., 2021). Sustainability is a multidimensional objective to maintain and improve societal conditions and ensure longevity of ecosystems and their functionality, as defined by generally accepted frameworks such as the United Nations Sustainable Development Goals (SDGs) (United Nations, 2015) or building on the Brundtland (1987) definition “meeting the needs of the present without compromising future generation meeting theirs”. Despite the progress defining the concept of sustainability and elucidation of environmental limits to socio-economic activity, holistic sustainability consideration is often lacking in decision-making within the Circular Bioeconomy transition (Giampietro, 2019; Kleinschmit et al., 2017; Székács, 2017). Consequently, attaining socio-economic goals at the expense of the environmental component are rife (Egenolf & Bringezu, 2019; Wohlfahrt et al., 2019). The difficulty of trading-off environmental objectives with socio-economic ones extends partly from simply omitting environment factors from an analysis in favour of technical and economic (Székács, 2017). Moreover, when environmental considerations are made, they typically emphasise reductionist methodologies, namely, focusing on narrowly selected variables such as carbon or GHG emissions, but ignore the complexity of social-ecological networks (O’Shea et al., 2022). It is therefore critical to emphasise the environmental constraints of economic activity, factoring in complexity and entirety of ecosystems, sourcing complementary methods to reductionist approaches of sustainability assessments for management of the Circular Bioeconomy transition.

The aim of this chapter was to identify and evaluate the trade-offs and potential risks to environmental sustainability (considered a pre-requisite for sustainable management) of the hypothetical case study from **Chapter 4.2.1** using a trade-off rule criteria and risk assessment using evidence synthesis and review.

5.2. Methodology

The trade-off and risk assessment process for this study was constructed around the topic of *“Environmental sustainability implications of developing seaweed aquaculture inside Hornsea wind farm over the next ten years”*

The assessment was bounded to the environmental component owing to resource limitations and prioritised evaluating the biophysical root of the socio-economic activity (seaweed aquaculture development) and preventing ecosystem degradation, a requisite for sustainability conclusions in bioeconomy evaluations (Giampietro, 2019). The trade-off assessment was performed using an adapted version of Bob Gibson’s trade-off rule system to systematically identify the environmental trade-offs and risk potentials of the hypothetical case study from **Chapter 4.2.1**. The trade-off rule system uses a set of objectives or requirements that a project must meet, and any effect or outcome counteracting said requirements is identified as a trade-off or risk potential (depending on severity of the trade-off) in the decision-making process (Gibson, 2012; Morrison-Saunders & Pope, 2013). The normative position of any innovation within the Circular Bioeconomy transition is the United Nations Sustainable Development Goals and thus the SDGs and objectives were inferred as the requirements for this assessment (Aguilar et al., 2019; European Union, 2018; Gawel et al., 2019). The UN SDGs are a collection of 17 sub-objectives that aims to define/ measure progress towards holistic sustainability (FAO, 2020; United Nations, 2015). The 17 goals cover the social, economic, and environmental domains and broken down into sub-categories with relevant targets and indices. To achieve the SDGs, progression of sub-objectives cannot be at the expense of others and must all be improved (United Nations, 2015). The environmental- focused objectives of the SDGs framework are outlined in Table 9 and were the basis of identifying environmental sustainability trade-offs.

Table 9- United Nations’ Sustainable Development Goals and related objectives

Environmental Focused United Nations’ Sustainable Development Goal	Objective of Sustainable Development Goal
13. Climate Action	“Take urgent action to combat climate change and its impacts”.
14 Life Below Water	“Conserve and sustainably use the oceans, seas and marine resources for sustainable development”.
15 Life on Land	“Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss”.

The requirements for this trade-off assessment are based on supporting the achievement of objectives within the United Nation Sustainable Development Goals. Any impact resulting from seaweed aquaculture development inside of Hornsea wind farm perceived to prevent or negatively contributed (opposite effect) to achievement of these goals would be defined as a trade-off- akin to the trade-off rules system proposed by Gibson (2012).

To evaluate the contributions to the environmental component of sustainability, the cognitive maps and impacts tables generated from completion of objective b and shown in **Chapter 4.3** were subjectively reviewed against each Environmental SDG objective including the sub-criteria of targets and indices within the broader objective, for perceived relationships. Said relationships were identified using related concepts or terminology between a potential impact from **Chapter 4.3** and the SDG objective or specific target. Impact relationships were categorised as either positive (supporting achievement of an objective), trade-off (counteracting achievement of an objective) or uncategorised with no explicit relationship perceived. Following the collation of impacts into supporting, undefined or trade-off categories for environmental sustainability sub-objectives, the trade-off potentials were further

characterised using an exploratory literature review of peer and non-peer reviewed sources to identify information available on the topic of a particular trade-off. Causal chains to illustrate trade-offs/ risk pathways were extrapolated from the existing conceptual maps (**Figure 14; Figure 15**) outputted in **Chapter 4.3.2**.

5.3. Results

The modified trade-off rules using SDG objectives identified seven potential trade-offs, seven positive and six uncategorised outcomes to environmental sustainability from developing seaweed aquaculture inside Hornsea Wind farm (**Chapter 4.2.1**). The consequence Table 23 summarises the relationships proposed between the impacts described in Chapter 4.1's abiotic and biotic maps (**Figure 14 & Figure 15**) and the objectives or targets of the United Nation's Sustainable Development Goals. For a full explanation of the trade-off paths and how they emerge, refer to supplementary materials ("impact tables (standardised)"). The SDG objective 13 to combat climate change was both positively and negatively affected by seaweed aquaculture development either through reduction of atmospheric carbon dioxide with reduced global warming potential because of added carbon sequestration at the site. Alternatively, increasing carbon emissions due to increased energy demand and combustion of fossil fuels extending from seaweed aquaculture activity (Table 23). The SDG objective 15 of protecting, restoring, and promoting sustainable use of ecosystems including halting biodiversity loss was also supported and negatively affected by seaweed aquaculture development. The impacts to SDG 15 revolved around supporting biodiversity through increased habitat complexity and biodiversity abundance extending from seaweed aquaculture, thereby preventing biodiversity loss in this instance. However, negative effects i.e. counteracting the objective included damage and increased mortality and assumed to amplify the loss of biodiversity directly and indirectly through seaweed aquaculture development (Table 23). The final SDG objective affected was 16 which focuses on sustainable marine environment with both positive impacts and negative impacts to marine life and abiotic components of the sea.

In some instances, the trade-off review process was also able to relate impacts supporting or counteracting achievement of specific targets including 14.1, 14.2, 14.3, 15.5 and 15.8 (Table 23). For the following impacts: seabed damage/ scouring; collision potential with wind turbine, behavioural adaptations including feeding prevention; attraction to site; disrupted and/or

reduced pelagic organisms' migration; disturbance and reduction to hydrodynamic flow; sunlight attenuation and seabed sedimentation (Table 23)- no links to the environmental-based objectives of the SDGs was clearly found and classified as uncategorised but assumed as a trade-off to facilitate further review.

5.3.1. Environmental sustainability trade-off and risk potentials

The impacts that were categorised into environmental sustainability trade-offs can be divided into 3 main themes, namely, trade-offs directly related to climate change (**Figure 21**), trade-offs to biodiversity and nature recovery, and trade-offs to the general conservation of marine environment (**Figures 22-Figure 26**). For full explanation of impact pathways, refer to **Chapter 4.3**.

The first of the environmental sustainability trade-offs/risk is amplifying Global Warming Potential (GWP) (**Figure 21**). The latest IPCC report explains the evidence on the risks of climate change to social and ecological systems around the world (IPCC, 2023). Current trends show atmospheric carbon exceeding thresholds for stable climate and the trajectory of climate change exceeding 1.5°C that is largely considered unsustainable owing to the widespread losses in human well-being and further destabilising ecological systems (IPCC, 2023). Therefore, any activity increasing carbon levels would thus contribute to the atmospheric load of carbon and be connected to the impacts of climate change.

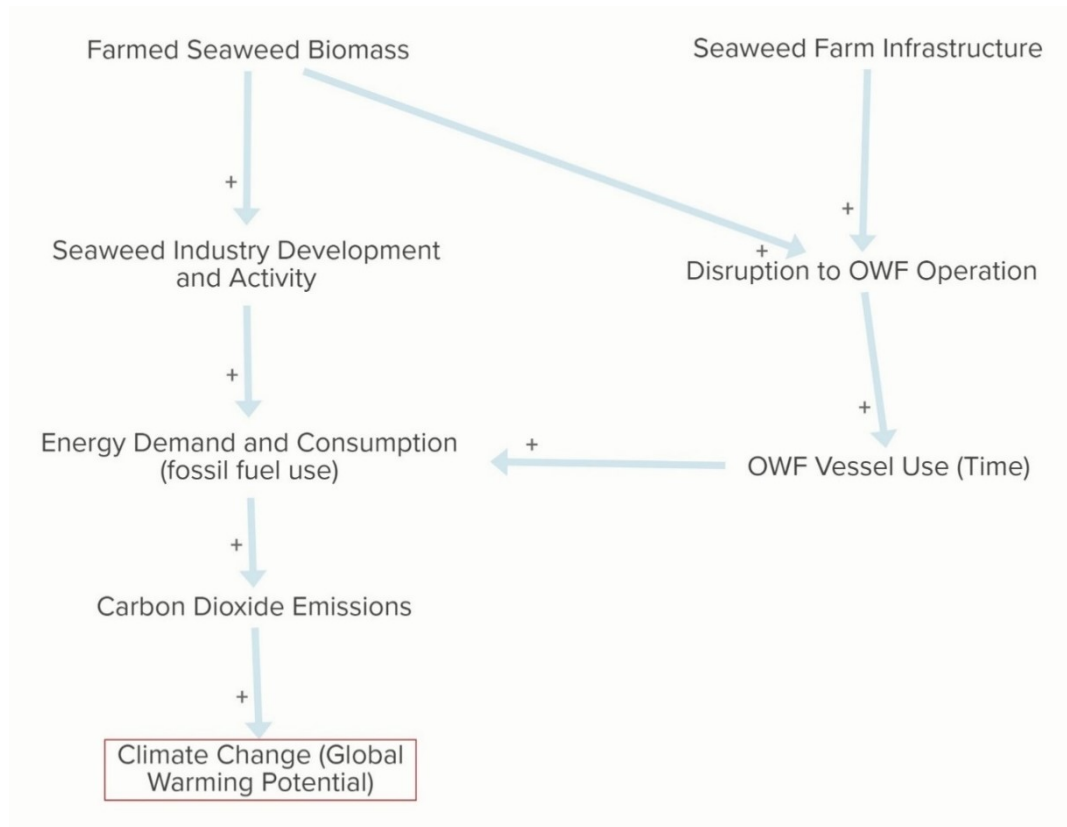


Figure 21- Causal chain for environmental sustainability trade-off/ risks with increasing climate change caused by seaweed aquaculture development inside Hornsea Wind Farm (extracted from **Figure 14**)

There are several factors and pathways negatively influencing the living components of the environment and this presents a trade-off or risk to ecological sustainability by developing seaweed aquaculture. The continuing decline in biodiversity levels causes risk to social-ecological sustainability and requires urgent intervention i.e. protection and recovery of natural habitats and biodiversity levels (Giampietro, 2019; IPBES, 2019; Leclère et al., 2020; Lotze, 2021). Addition of seaweed aquaculture inside Hornsea wind farm will potentially limit the opportunities for natural recovery of the seabed (**Figure 22**) and thus, reduce potential gains needed in biodiversity restoration (Lotze et al., 2011). Evidence indicates that organic material will be released from the farming of seaweed biomass and may add to sedimentation rates and changes to benthic composition (**Chapter 4.3**). However, release of organic material is dependent on the seasons of cultivation and stages i.e. maintenance or harvesting, as described in Campbell et al (2019). Furthermore, change in hydrodynamics is evident with the added

infrastructure and seaweed cultivar in the water column raising sedimentation rates and perceived to prevent seabed recovery opportunities (Bruhn et al., 2020; Campbell et al., 2019). The severity of these changes will depend on the scale, type of infrastructure, biomass, and the baseline characteristics of where the seaweed farm is located with current nearshore farms using a long-line technique (Bruhn et al., 2020). As the development of seaweed aquaculture inside wind farms is still conceptual, there is no available data on the severity of wave attenuation or rate organic material release meaning the scale of effects is uncertain and probabilities on the added chain of impacts is also unknown including the fate of organic material once released from the farm and how this relates to detrimental effects on seabed conditions.

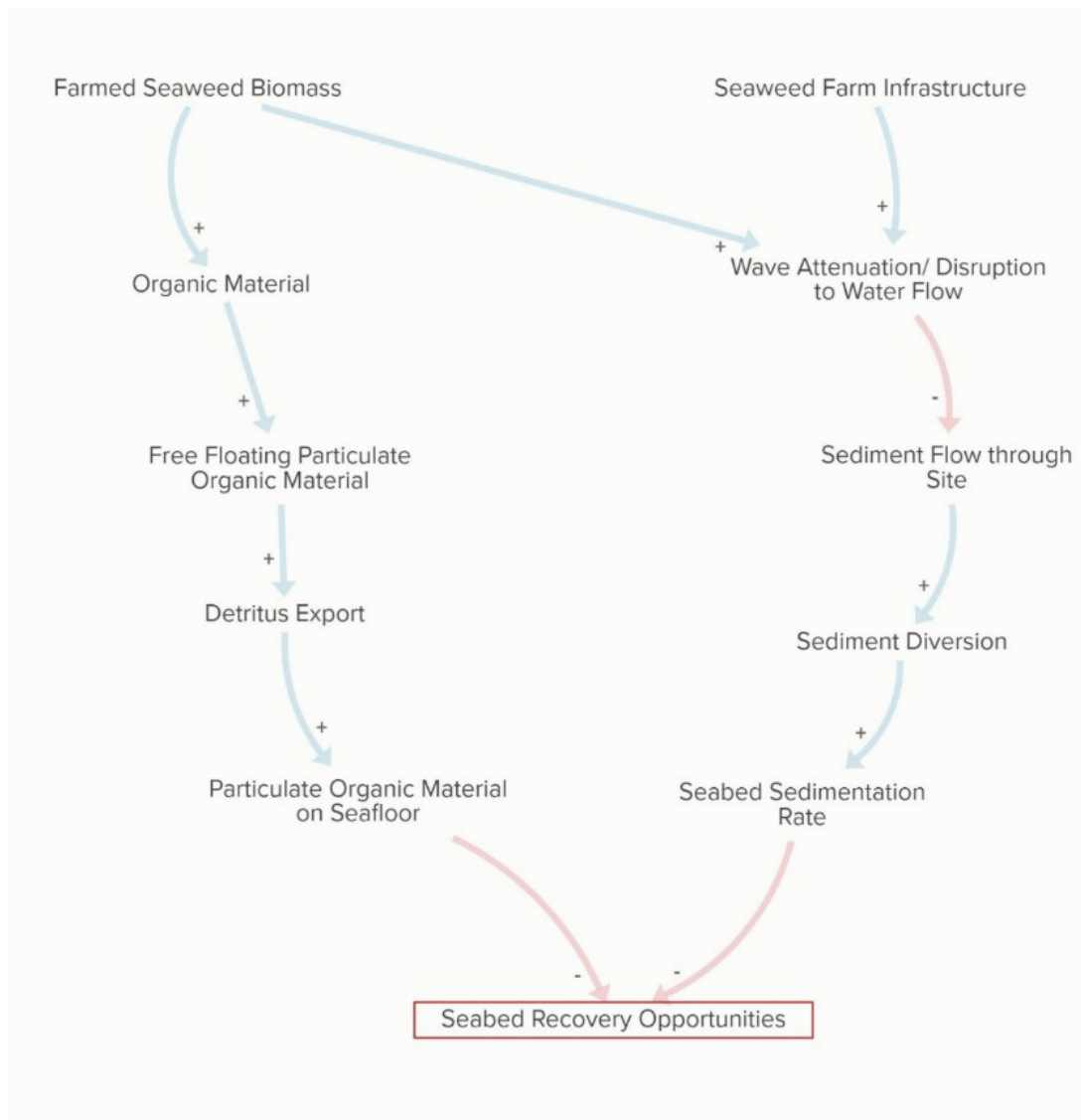


Figure 22- Causal chain of environmental sustainability trade-off/ risks resulting inhibition of seabed recovery owing to seaweed biomass and farming infrastructure if sited within Hornsea Wind Farm (extracted from **Figure 15**).

The loss and damage to existing marine biodiversity is an additional threat to environmental sustainability resulting from several knock-on effects of seaweed aquaculture development. The cause of this effect firstly stems from the 3D structure (farmed biomass and artificial rig) created in the water column subsequently causing loss of benthic communities owing to the reduced sunlight access; formation of an obstacle with entanglement potential of pelagic organisms and the added surface area utilised by epifaunal species that are then removed at the harvest stage (**Figure 23**). Evidence has shown nearshore seaweed farms to attenuate sunlight-equalling 40% at 5m during peak biomass levels- and will carry over to any type of seaweed farm, on or offshore (Bruhn et al., 2020; Campbell et al., 2019; Visch et al., 2020). The

likelihood of knock-on effects is uncertain and dependent on the baseline characteristics of the seabed and benthic community, the siting of infrastructure in addition to scale of farming. Moreover, there are currently no recorded incidences of pelagic organisms entangling in seaweed farm infrastructure, but this doesn't necessarily negate entanglement potential, especially, with expansions into new areas (Campbell et al., 2019). Environmental impact assessment reports for Hornsea wind farms identified higher level trophic organisms are active in the area making interaction with the seaweed farm plausible with the following species already recognised as receptors to existing development: Harbour porpoise; White-beaked dolphin; Minke whale; Harbour seal and Grey seal (Orsted, 2018).

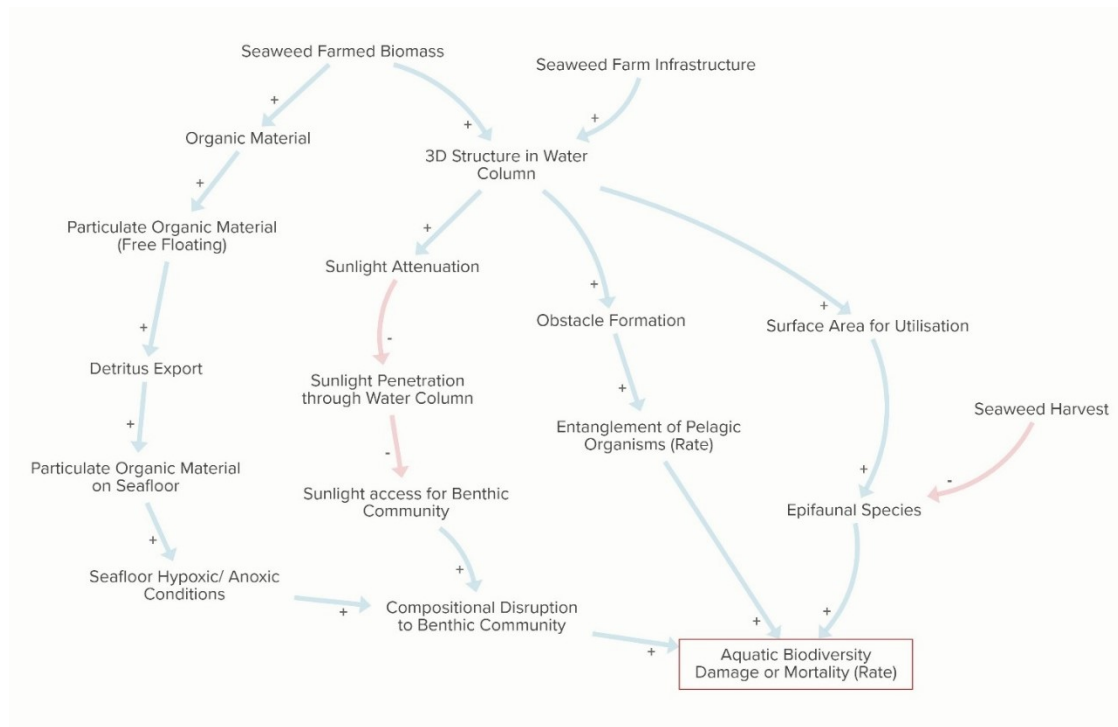


Figure 23- Causal chain of environmental sustainability trade-off/ risk extending from seaweed aquaculture development inside Hornsea wind farm with increased damage or mortality of biodiversity (extracted from Figure 15).

The second cause of direct trade-offs to aquatic biodiversity results from the farmed seaweed biomass, with the release of organic material causing hypoxic and anoxic conditions on the seafloor leading to disruption to the benthic community (**Chapter 4.3.2**). Evidence for this impact relates to the description above on sedimentation rates and, again uncertain given the lack of information on the benthic community characteristics at the site. The final effect with implications for directly lowering biodiversity levels is the reduced marine nutrient levels causing an overall loss in the stock of biomass with reduced food web dynamics (**Chapter 4.3.2**) (**Figure 24**). The absorption of free-floating chemicals (nutrient) is well documented and thus, highly likely to occur and hence, may lower overall nutrient levels in the ecosystem (Roleda & Hurd, 2019). The extent to which reduction in nutrients induces competition with natural photosynthetic organisms is less certain, however, modelling tools are available and would need further characterisation given the different contexts/ case study (Aldridge et al., 2021; Wood et al., 2017).

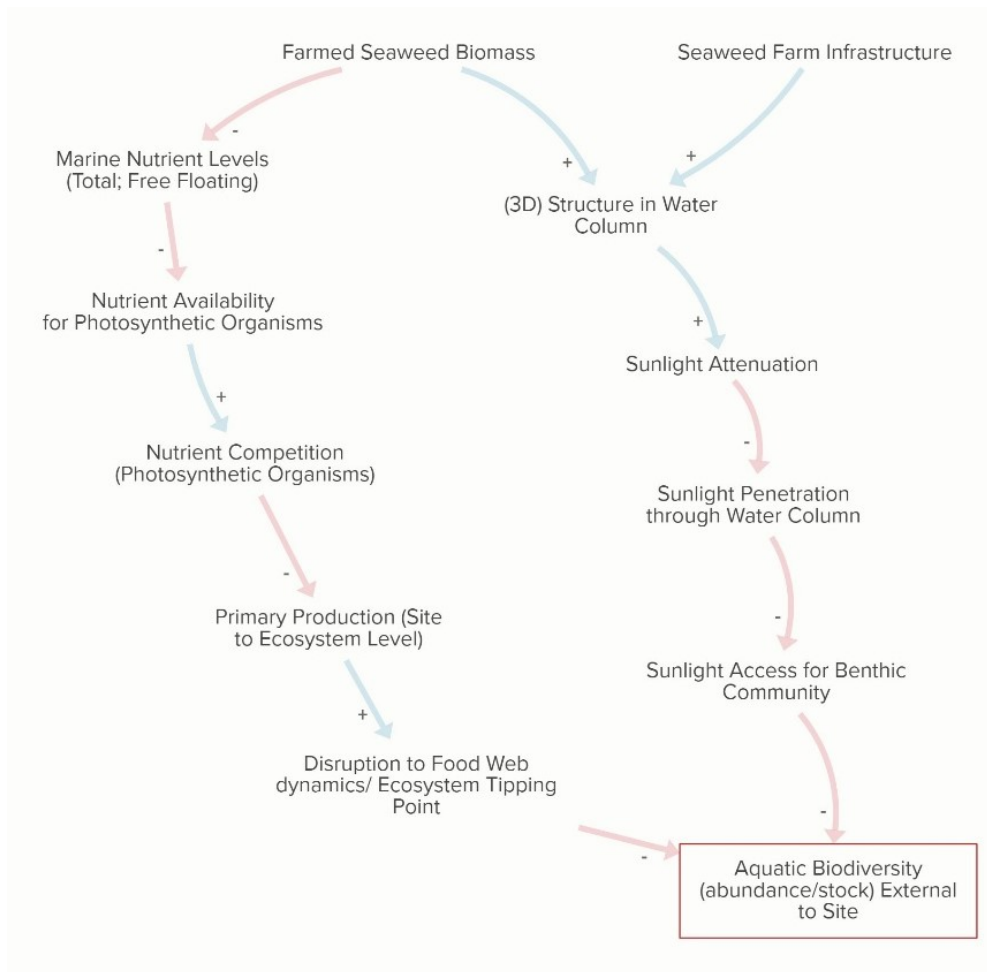


Figure 24- Causal chain of events relating to environmental sustainability trade-off/ risk resulting from seaweed aquaculture development inside Hornsea wind farm with loss in aquatic biodiversity stock external to site (extracted from Figure 15).

Further trade-off and risk potential to the conditions of marine biodiversity in the area may derive from the non-native species and augmentation to marine bacteria and viruses introduced by seaweed aquaculture inside Hornsea including the farmed biomass-alone and the combination of the infrastructure and seaweed (**Figure 25**). Invasive species are defined as organisms that are not native to a specific habitat- terrestrial or aquatic- often threatened existing species in a variety of ways and by extension, the stability of an ecosystem (Hou et al., 2023). The types of negative effects resulting from an invasive species typically include excess predation beyond long term trends and spread of disease that can also lead to reduction in organismal density and the diversity of ecological communities (Linders et al., 2019). Consequently, the complex mix of effects can significantly alter the ecosystem dynamics and

with it, the functionality of the area making it a potentially severe consequence to biodiversity sustainability.

The introduction of non-native species into marine habitats from seaweed aquaculture development may derive from two main areas, firstly, the 3D structure in the water column may provide an added surface area to support translocation of non-native species (**Figure 25**). No recorded incidences have been found of this effect with seaweed aquaculture but moving to offshore environments could increase the likelihood of this impact. Having been flagged as a concern already with the presence of monopile structures of wind farms (Langhamer, 2012; Lloret et al., 2022; Wood et al., 2017). Furthermore, the attenuation of waves and disruption to hydrodynamics was perceived to augment the viral and bacterial composition/ dynamics of an area (**Chapter 4.3.2**). Carrying concerns for unknown changes to ecological dynamics including disease risk, however, evidence is limited on the severity or likelihood of this effect (**Chapter 4.3.2**). Additionally, the seaweed biomass being farmed may release spore material as part of the life cycle of the organisms (Campbell et al., 2019) and thereafter the spores from the farmed biomass may establish and interact with natural populations and alter the genetic composition (**Chapter 4.3.2**) (**Figure 26**). Farmed organisms may undergo selective breeding to reduce the genetic diversity with the aim to make certain phenotypic properties more likely and/or enhanced such as faster growth rates, higher protein concentration and so on (Khan et al., 2023). Constraining genetic diversity of species and populations has been shown to threaten the resilience of a species to survive perturbations in environmental parameters such as temperature change, exposure to viruses and more (Christmas et al., 2015; Griffiths et al., 2020; King & Lively, 2012). Therefore, if farmed seaweed biomass were to establish and has constrained genetic diversity which spread or dominated the natural populations, this may imply severe issues to the resilience of existing natural populations (**Figure 25; Figure 26**).

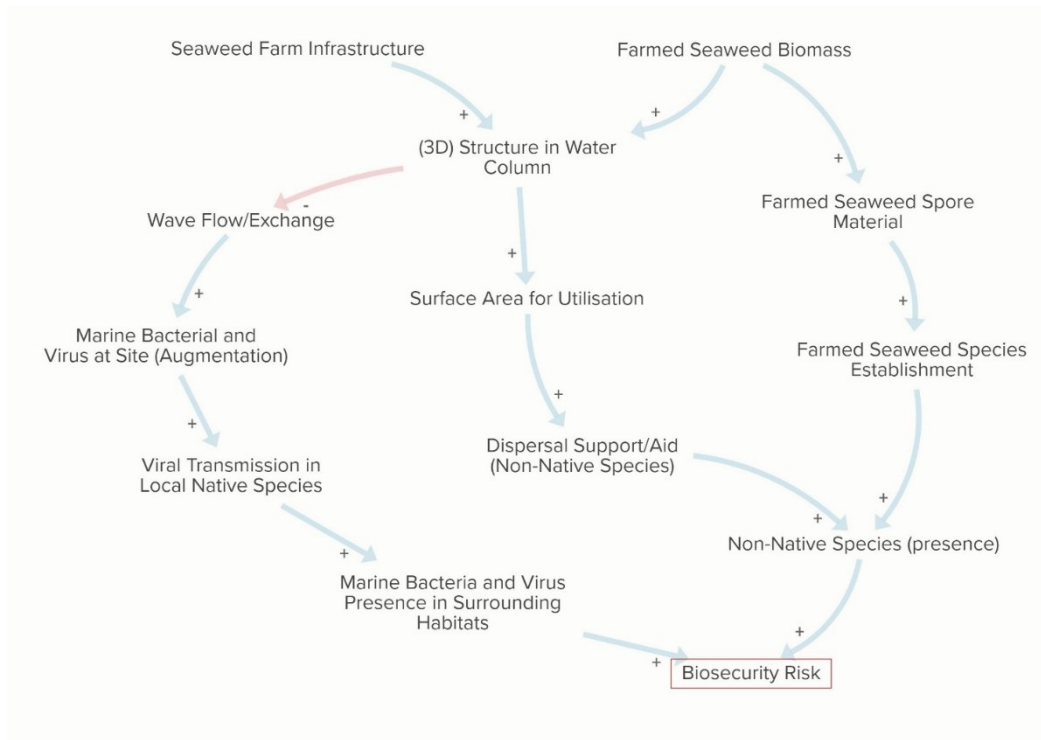


Figure 25- Causal chain elucidating environmental sustainability trade-off/risk created by seaweed aquaculture development inside Hornsea wind farm with added biosecurity risks to marine habitat (extracted from Figure 15).

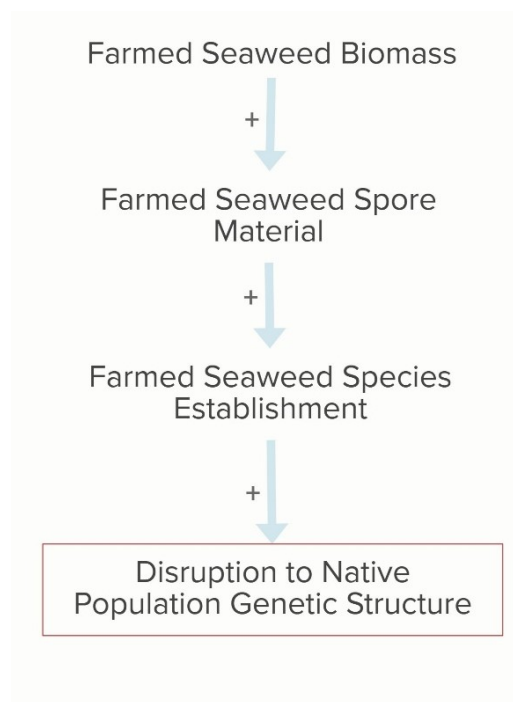


Figure 26- Causal chain of environmental sustainability trade-off/risk extending from seaweed aquaculture development inside Hornsea wind farm with disruption to Native Population Genetic Structure (extracted from Figure 15).

The remaining impacts, although not categorised as no direct link was perceived, may be considered as trade-offs to the general objective of conserving the marine environment as part the SDG objective 14 to “conserve and sustainably use marine resources” (United Nations, 2015). For example, the raised collision potential of avian organisms with wind turbines didn’t necessarily create any threat to biodiversity levels as a result of raised mortality, however, this may be due to the language used at the time of developing impacts and conceptual maps in **Chapter 4.1 (Figure 15)**. If assuming collisions resulted in the mortality of the organism, this could then become another trade-off to the protection of biodiversity and/or restoration efforts of ecological communities. However, the scale and severity of the impact is unknown with no case studies available. Similarly, behavioural changes of avian organisms should be further considered with the restriction of feed/foraging capacity which may constrict the food supply for species and thus, impede restoration or reduce avian biodiversity levels (**Chapter 4.3.2**). The damage to the seafloor was also uncategorised with no knock-on effects or linkage to SDG objectives explicitly, but the scale and severity of the effect would need further review. Finally, disruption to pelagic migration did not imply a direct threat to either protection or restoration of biodiversity levels. However, established migration patterns are crucial to the survivability

of species so that if disruption impedes the movement of organisms for feeding and breeding purposes, this could likely reduce the continuation of effected species which are active in the area as described by the Hornsea Environmental Impact report (Orsted, 2018).

5.4. Discussion

Optimising the benefits and limiting negative environmental impacts of seaweed aquaculture development will be critical to acceptance, especially, in the MUS context and the need for enhancing social-ecological sustainability (van den Burg et al., 2020a; van den Burg et al., 2020b). Using the findings from **Chapter 4.3.2**, combined with an assessment process adapted from Bob Gibson's (2012) trade-off rules and evidence review, the potential environmental sustainability trade-offs alongside positive effects of coupling seaweed aquaculture and a wind farm were identified. It's clear that development of seaweed aquaculture inside of a wind farm carries significant trade-off potential to the global environmental sustainability policy goals such as the UN SDGs. Having performed this sustainability appraisal, major implications were found to include threatening whole biodiversity networks, exasperating climate change and limiting efforts for the general conservation of the marine environment. Available information was used to characterise the selected risk pathways. However, opportunities to mitigate and uncertainty about the trade-offs is still present and will have significant bearing on future decision making around the MUS.

Environmental trade off and risks in co-locating seaweed aquaculture and wind farms

Mitigating risks to ecological systems in Blue Economy development is a key priority for successful management (Hodgson et al., 2019). As recommended in **Chapter 4.4**, Bayesian Belief Networks and use of expert judgement is a method to evaluate several of the impacts of MUS development with limited data, by generating conditional probabilities between the connected variables (Kaikkonen et al., 2021). However, **Chapter 4** had not indicated what trade-offs and risks needed to be evaluated and why (**Chapter 4.4**). This study then builds on the cognitive maps, where it may be challenging or unnecessary to evaluate all impact pathways. Instead, the use of trade-off rules provided a systematic method to demonstrate key priorities to consider, namely, environmental trade-offs and risks, if one were to operationalise the MUS. This study also brings into question the sustainability claims of the MUS that are simplistic and do not account for the nuances of development. For example, claims of

biodiversity conservation promoted through co-locating seaweed aquaculture and lower trophic aquaculture more broadly, with wind farms (Przedrzymirska et al., 2021) is an oversimplification, suggesting an absolute outcome. The problem here lies in pursuing co-location of seaweed aquaculture and wind farms with the belief of attaining conservation objectives and instead, introducing any of the threats identified by this study (Table 23) that compromise marine conservation.

Another major finding of this work was extending the risk catalogue that was attributed to co-location of seaweed aquaculture and wind farms by a previous study. In van den Burg et al (2020a) risks were elicited from “experts” and did contain parallels with this trade-off review including reducing primary production levels in ecosystems and raising mortality to avian species. However, this study extended up these catalogues with, firstly, augmentation to bacteria and viral composition and knock-biosecurity risks, genetic restructuring and more broadly, exasperating climate change (Table 23). A further difference was that primary production was considered “low risk” in the aforementioned study, in contrary, this trade-off review suggests that stakes may be much higher with potential to induce an ecosystem tipping point and thus counteract global policy priorities (**Figure 24**) (United Nations, 2015).

The trade-off review and use of the SDG objectives provided a novel way to link the impact tables from **Chapter 4.3** with the broader policy aims of the Circular Bioeconomy, namely, enhancing social-ecological sustainability (European Union, 2018). The assessment process identified where the environmental sustainability trade-offs or risks in the decision-making process exist. However, the process would need to be continued to meet the holistic sustainability as the study excluded the social and economic objectives due to resource limitations. Bob Gibson’s trade-offs rules system is a valuable method to conceptualise sustainability trade-offs in project development, however, is limited to qualitative outputs in the approach I used (Gibson, 2012). The trade-off review used evidence sources that can indicate the severity and make assumptions about the likelihood of certain effects if they were to result based on related information/ case studies. However, the impact probabilities including likelihood and severity of the environmental risks, remains uncertain and will largely be resolved only by data generation and modelling exercises such as Bayesian Network as suggested above. Nonetheless, having performed a systematic evaluation, priority consequences with severely negative implications to the environmental sustainability have been brought to the forefront of the decision-making process, nonetheless.

The sustainability assessment process is a valuable appraisal method to determine the sustainability (gains and/or losses) of an activity, but the conclusions made are always influenced by the external context (Sala et al., 2015). Social-ecological systems are described as complex and open and therefore in a state of flux (Preiser et al., 2018). The results at the individual level including the MUS, will be continually changing and need continuous review among external changes (Morrison-Saunders & Pope, 2013). The MUS case study proposed in **Chapter 4.1** is placed within the context of the North Sea environment. If overall biodiversity continues to decline in the territory as recorded (Capuzzo et al., 2018; Weinert et al., 2021), the potential biodiversity gains made as part of seaweed aquaculture development will become more important. This will also be the same case with carbon emissions, if sudden reductions are made in the total load of atmospheric carbon, then positive emissions from the seaweed supply chain of the proposed case study may become more acceptable. It is therefore important to review the MUS regularly and place within the overall context of the “green transition” being envisioned by societies whereby ecological sustainability is promoted on multiple fronts capturing the totality of efforts to enhance social-ecological sustainability from biodiversity protection and restoration to development of less environmentally harmful socio-economic activity (D’Amato et al., 2017; Loiseau et al., 2016; Zhai et al., 2022).

Mitigating trade-offs and risks in co-locating seaweed aquaculture and wind farms

Despite the negative consequences and the severity of the trade-offs that could result, opportunities to alleviate the problems are possible. Although, two pathways may increase carbon emissions from seaweed aquaculture development (**Figure 21**), the farmed seaweed will also sequester carbon (Laurens et al., 2020) and the processing of seaweed into products may displace fossil-based counterparts in the economy, thus balancing the carbon budget (**Figure 17**). To understand whether the seaweed supply chain contributes to or reduces the atmospheric carbon, development of seaweed aquaculture inside wind farms, Lifecycle Assessment (LCAs) need to be performed whereby carbon input and outputs of the entire process are quantified and linked to Global Warming Potential (GWP) (Muralikrishna & Manickam, 2017). Example LCAs to evaluate seaweed process systems include Nilsson et al (2022) and Seghetta & Goglio (2020) and have theoretically concluded reductions in carbon dioxide levels. However, these are quantified outside the MUS context and exclude important social-ecological factors as described in **Chapter 4** including loss of existing carbon sequestration and disruption to wind farm vessels with added combustion of fossil fuels (O’Shea et al., 2022). In the case of a positive GWP resulting from the seaweed supply chain,

a mitigation option will be to utilise low-to-zero carbon energy in the supply chain when feasible (upstream production and/or downstream processing) as suggested in Zaky et al., (2021) and/ or use carbon offsets governed by adequate regulations (Fankhauser et al., 2021).

The results of **Chapter 4** and this trade-off assessment highlight the positive gains to biodiversity networks with tentative capacity to increase the abundance/ stock of biomass with added ecological complexity in the area (**Figure 15** & Table 23). Therefore, if negative biodiversity impacts are significantly reduced or mitigated all together, this may enhance environmental sustainability in the region with the added ecological functionality promoted from structural habitat complexity extending from seaweed farms (**Figure 15**). One of the primary causes for adverse effects to biodiversity is on account of the added 3D structure in the water column (**Figure 15**). Options to characterise the impact uncertainties include hydrodynamic flow models to simulate the dampening effect at the site with farming infrastructure and compared with baseline characteristics- similar to hydrodynamic evaluations conducted during deployment of monopile wind turbines (van Berkel et al., 2020). Rates of sunlight attenuation may also be calculated from the additional 3D structures (Aldridge et al., 2021). Following these, ecological analysis/ simulations such as population viability analysis, would be recommended to understand how changes in environmental parameters including wave attenuation, sedimentation rates and loss of sunlight, may influence the requirements of the benthic community, pelagic and/or avian organisms (Chaudhary & Oli, 2020; Kelly et al., 2013; Woodruff, 2001). Any loss in species should be evaluated against the gains that could be made from the development, compensated with mitigation options including the designs of infrastructure, monitoring programs of key variables. Biodiversity offsetting may also be considered as a last resort but subject to a full transparent consideration of the strengths and limitations of this policy- see Droste et al (2022) and Gonçalves et al (2015) for further commentary on biodiversity offsetting. Several of the changes to child nodes in the conceptual maps will unlikely have relevant information so the scale, likelihood and severity of the threats will remain difficult to determine.

Completing an initial trade-off evaluation has progressed the Decision Analysis procedure i.e. trade-off/ risk characterisation for the MUS (Hemming et al., 2022). Further research as part of Structure Decision-Making process in the MUS should include the alternative decision choices and comparing with the findings of this chapter in addition to **Chapters 3** and **4**. Furthermore, the identification of trade-offs is an important step to direct future modelling, development of monitoring and management frameworks that supports pilot studies- real or

simulated. The trade-off and risk appraisal has also linked the Multi-use Setting to the broader sustainability management criteria for an innovation in the Circular Bioeconomy transition. The progress made on evaluating the social and ecological implications of the MUS is critical to acceptance of the concept projects (van den Burg et al., 2020a; van den Burg et al., 2020b). Notwithstanding, if an economically viable production model cannot be devised then the value of the findings will be significantly reduced so it is recommended concentrated efforts must be made towards this aim. Ensuring the fullest value of **Chapters 3, 4 and 5** findings are realised.

Limitations

The use of SDGs provides collectively agreed objectives- via the UN system- to infer the sustainability of an activity or not. Nonetheless, the assessment process is still a subjective interpretation by a single author and my bias will influence the outcome of results including selection of trade-offs and risk potentials and subsequent characterisation based on personal knowledge of the subject. On the other hand, a review procedure would typically utilise a review panel of experts/ relevant parties to evaluate consistency of outputs e.g. selection and scrutiny of evidence, during environmental assessments to increase validity of results (Collins et al., 2015; James et al., 2016). Additionally, relevant parties such as local community, regulators etc, must be consulted throughout the assessment process as prescribed in Bob Gibson's original trade-off rules, but had to be excluded from this study owing to resource constraints (Gibson, 2012, 2013). Follow-up with relevant parties must therefore be made in subsequent investigations to agree/ disagree on all project objectives and engaged throughout the evaluation process in reaching consensus about positive and/or negative outcomes of a project. More broadly, despite attempting to define what sustainability is using SDG objectives and indices, these are nonetheless bias in themselves thwart with political problems and lack of adequate scientific definition- see Arora-Jonsson, (2023) for further commentary. Further use of trade-off assessments would then need to build on these objectives such as reducing ambiguity in statements and having a formularised metric built from current natural laws and theory in environmental sustainability.

5.5. Conclusion

The sustainability trade-off and risk review characterised the environmental sustainability implications of developing seaweed aquaculture inside Hornsea wind farm. The coupling of seaweed aquaculture and a wind farm appears to positively contribute to multiple sub-objectives of environmental sustainability including biodiversity enhancement and combatting climate change. On the other hand, trade-off potentials do exist with major implications to biodiversity networks, climate and conservation that must be further assessed and mitigated to optimise the social-ecological benefits of seaweed aquaculture-wind farm development. The research dramatically improves the risk dialogue in the MUS including counteracting previous dismissal of trade-offs and building out the catalogue of concerns. It is therefore recommended further examinations using quantitative methods such as Bayesian Network analysis combined with structured expert elicitation be deployed to priority threats to environmental sustainability for effective management in seaweed aquaculture-wind farm development. Further research at management level includes assessment of physical and ecological changes to determine the degree of risk including likelihood and scale of impacts. It is also important to continue characterise the sustainability implications with improvements to discussed limitations of this study, namely, consulting relevant parties and adding further structure to the definition of sustainability. Regular reviews will also be important during the management of coupling seaweed aquaculture and wind farms. With this study, the impacts and sustainability implications of the MUS are becoming clearer. Nonetheless, these findings must be complemented with sufficient investigations and deployment of robust economic strategy to realise its full potential and is explored in the following chapter.

Chapter 6

Commercialisation of the MUS via industrial seaweed process system development

6.1. Introduction

The cognitive mapping of subject matter experts in **Chapter 4** demonstrated the high variability about the perceived economic outcomes from a hypothetical MUS including a risk of debt from commercialisation due to a lack of certainty in economic viability of business model(s) (van den Burg et al., 2016; **Chapter 4**). Unless the economic challenges are resolved for offshore seaweed aquaculture, implementation and socio-economic sustainability in real-life circumstances is incredibly unlikely in the first instance (Van den Burg 2020b). Given the severity and uncertainty of consequences from co-locating seaweed aquaculture and wind farms, it was recommended an alternative strategy is devised whereby nearshore seaweed aquaculture and industrial process systems are first implemented to improve operational understanding before moving production into offshore MUS conditions (**Chapter 4**). However, to those ends, suitable industrial process designs will be needed and must have the capacity for moving processes into offshore MUS (**Chapter 4**), namely, scalable technologies and biorefinery innovations- as suggested in Van den Burg et al (2016). The aim of this chapter was therefore to develop an industrial seaweed processing system with the feasibility to scale-up in offshore MUS such as the hypothetical case study of **Chapter 4**. Attempting to advance the implementation of a MUS innovation with an appropriate operational strategy in support of techno-economic decision-making under uncertainty.

6.1.1. The Economics of Seaweed

Seaweed has long been a source of food for humans with evidence of consumption dating back 14,000 years (Buschmann et al., 2017). Seaweed species are today widely traded and consumed for a variety of culinary purposes including salads, seasoning, whole food, snacks and more (Dillehay et al., 2008; Padam & Chye, 2020), and demand for macroalgae biomass is expected to continue rising in the next decade (Hochman & Palatnik, 2022). Seaweed biomass has a diverse chemical composition: rich in sugars, pigments, antioxidants, proteins, vitamins, lipids, sterols, and minerals, and can fulfil many different needs to those of high value such as

pharmaceutical, nutraceutical, cosmetic and food/feed to those of lower value including energy, and agricultural (Balina et al., 2017; Padam & Chye, 2020). Seaweeds are already a valuable feedstock used in biochemical manufacturing with different seaweed species- red, brown, and green- processed depending on the targeted compound/ product(s) (Torres et al., 2019). Commonly extracted products from seaweeds are the hydrocolloids including alginate, agar and carrageenan, and other polysaccharides such as fucoidan (Torres et al., 2019). Today, the extraction of hydrocolloids is largely dominated by chemically intensive techniques that relies on time and solvents including alkalis, acids, and formaldehyde, to remove a desired compound (Saji et al., 2022). However, the use of chemical-based methods for seaweed biopolymer production leads to environmental problems with the generation of hazardous waste and contains manufacturing inefficiencies such as extended timelines to end product and loss of other high value material (Lomartire & Gonçalves, 2022; Silva et al., 2017). Even before members of the UN had obligations to ensure that all human activity is economically, environmentally, and socially sustainable as directed by the UN SDGs, an objective in chemical manufacturing has been to reduce and even eradicate all forms of environmental pollution and the detrimental effects in the supply chain, defined as “green chemistry” (Clark, 1999; González-Garay et al., 2021).

Ideal chemical synthesis in green chemistry is defined as processes that are simple, atomically efficient, safe, only require one step, have no wasted reagents, are environmentally acceptable, use all available materials and result in a 100% yield of the target element/ compound (Clark, 1999). Application of new technologies and development of protocols aiming to meet the criteria of green chemistry namely, reducing use of non-renewable resources, solvents, and waste, have been considered for macroalgae processing. Technologies and techniques that have been applied claiming to enhance sustainability by aiding chemical extraction from seaweed feedstocks include use of Microwaves, Ultrasound, Supercritical Fluid, Pressurised Solvent, Enzyme, Subcritical Water, Pulsed Electric field and Gallic Acid Equivalent techniques/technologies (Matos et al., 2021). Moreover, the enabling technologies for new manufacturing processes aiming to meet sustainability objectives may be combined with the principles of biorefinery or biorefining that may reduce pollution further and promote economic efficiency in chemical manufacturing (Baghel, 2023).

Seaweed biorefinery defines a process that uses a cascading approach to extract multiple products per unit of feedstock as all waste streams becoming valorised (Torres et al., 2019). The proposed advantages of using a seaweed biorefinery is that maximum value can be derived

per unit (e.g. kg) of seaweed biomass owing to the multiple product/ income streams that are created (Baghel, 2023; Balina et al., 2017). Moreover, circularising the biomass in a process aims to reduce the levels of biowaste associated with Bioeconomy activity as waste streams are re-processed instead of disposed of into the environment. Establishing a seaweed biorefinery system has been identified to improve the economics of integrating seaweed aquaculture inside a wind farm (van den Burg et al., 2016). However, design of a seaweed biorefinery including the process technologies, that are economically viable and applicable to a MUS case study of **Chapter 4.2.1**, would need to be determined. To that end, techniques drawn from chemical/ biological engineering may be useful in determining an appropriate process system (Bakshi, 2019).

6.1. Process systems design and evaluation

Initiating or revising existing supply chains in the Bioeconomy is a complex challenge and needs to involve a variety of actors and methodologies including computational modelling, at different stages to integrate and apply diverse expertise (Lask et al., 2017). Process engineering provides an integrative framework that can connect biological, chemical, and physical domains in addition to linking with the wider context of sustainability in the supply of goods and service (Bakshi, 2019). In the first instance, understanding the economic viability is critical in the implementation of any industrial process or service as profitability will be the primary incentive for investment into construction/ operation of a manufacturing plant (Buchner et al., 2018). Techno-economic assessment (TEA) is the most widely used approach to evaluate the economic viability of an activity which involves designing and simulating a chemical manufacturing process followed by calculation of the net profit potential (Faber et al., 2021). Techno-economic evaluation commonly uses the Net Present Value (NPV) formula- a Discounted Cash Flow analysis whereby profit potential (i.e., currency value) is calculated using the sum of the cash flow minus the initial investment costs and accounting for value depreciation (discount factor, %) over the lifecycle of an activity (days/ months/ years) (Žižlavský, 2014).

To commence with TEA, conceptual process designs of a (bio)chemical manufacturing system including the technologies or practices used, must be available. This is to enable modelling activity including process simulations, and then to estimate costs and revenue flow for a given

manufacturing plant (Buchner et al., 2018)- equating to a Technology Readiness Level² ranking of 3 or above. In order to present such designs, advanced theories in systems engineering suggests the design procedure should be a multiphase and iterative scheme- initiating with creation of a baseline design- to enhance desirable features in the system including flexibility whereby an engineered system has inbuilt capacity at the point of design to better respond to changing circumstances e.g. economic price fluctuations (Cardin, 2014). The idea of ensuring flexibility in the engineering of systems is advantageous over typical design and assessment methods as the engineered system can better cope with the dynamic environment (social-ecological) it's set within and thus has wider operating conditions to mitigate risks or downfalls in the project design/functions (Cardin et al., 2015). Potential options to enable designs include C-K Design theory, in that a concept e.g. biorefinery system, and knowledge space e.g. technical documentation, experts and so on, is explored to generate configurations of a system design (Cardin et al., 2015; Vourc'h et al., 2018).

Given the lack of technical and economic including strategic, information regarding integration of seaweed aquaculture and offshore wind, the use of TEA will be particularly valuable in the context of the MUS. As currently stands, it is difficult to determine what and if any industrial process and economic outcomes are viable or likely if progressing with implementation (**Chapter 4**; Van den Burg et al., 2016; Abhinav et al., 2020). Consequently, inertia in commercialisation of the MUS will continue until greater certainty in economic decision making is made.

In this chapter, a techno-economic assessment of a seaweed industrial process system with implications for scaling-up production in offshore wind site was performed. The first objective of this research was to propose an industrial seaweed process system design that had the ability of scaling-up production inside the Hornsea wind farm site. A second objective was to investigate the economic viability of said system to understand the feasibility of implementing the infrastructure and business model in real-life circumstances. In this techno-economic analysis, information drawn from literature and stakeholders was combined with Excel modelling to characterise the selected process system. Simulation results were used to estimate

² Technology Readiness Level (TRL) is a measurement method proposed by the National Aeronautics and Space Administration (NASA) and widely adopted to define the technology maturity of an innovation from 1 to 9 with 9 representing a mature technology ready for deployment at industrial scale (R. M. Brown et al., 2022)

outputs at each stage and determine the size and performance of process equipment that fed into NPV calculation for elucidate profitability in different scenarios.

6.2. Methodology

A techno-economic assessment (TEA) was conducted to design and explore the economic performance of an industrial seaweed process system with strategic implications to the MUS scenario proposed in **Chapter 4.2.1**. As data is limited for offshore seaweed aquaculture and processing (van den Burg et al., 2016), the focus of the study was bounded to nearshore seaweed aquaculture, a relatively mature production activity for the UK evidenced by active commercial enterprises (Norfolk Seaweed, 2022; SeaGrown, 2023) and advanced seaweed production models (Van Der Molen et al., 2018). Implementing in nearshore circumstances is also assumed to improve operational certainties including financial performance, in moving to offshore conditions where high degrees of uncertainty persist in decision-making (**Chapter 4**). The TEA was performed using guidance drawn from literature on techno-economic evaluations in chemical, biological and mechanical engineering disciplines as referenced in the following sub-chapters. The purpose of the TEA was to design and evaluate the net present value (£) over the lifecycle of a seaweed processing system. The TEA was bounded to an 8-year timeline based on meeting the 2030 deadline of achieving the Sustainable Development Goals. The final seaweed process system design needed to have consideration of the hypothetical case study as part of the alternative strategy proposed in **Chapter 4.4**, namely, feasibility for developing and scaling up production within the Hornsea Wind Farm array. The following sections describe the stages of the techno-economic evaluation including conceptualising a process system design, process parameterisation and simulation and finally, profitability analysis including performance sensitivity.

6.2.1. Conceptual bioprocess design

To perform a techno-economic assessment in chemical/biological engineering, conceptual process designs of manufacturing systems must be available (Buchner et al., 2018). The first objective of this assessment was therefore to source/design a conceptual seaweed biorefinery process system relating to the hypothetical case study of Chapter 4.2.1. To initiate the design process, requirements are needed whereby specifications are set to propose system concepts (Elm et al., 2008). For this assessment Table 10 details the system specifications and justifications I proposed based on policies and technical feasibilities extending from the hypothetical case study (**Chapter 4.2.1**).

Table 10- Key requirements proposed to guide design of seaweed process system for techno-economic assessment.

System requirement	Justification
Sugar Kelp (<i>Saccharina latissima</i>) feedstock	Seaweed organism with a demonstrated capacity for offshore aquaculture in the North Sea (Buck et al., 2017; Buck & Buchholz, 2004)
Scalable: techniques/technology/ process	The process can scale-up with increasing inputs of biomass from larger production areas including from aquaculture located inside a wind farm (Troell et al., 2009; van den Burg et al., 2016)
Biorefinery capacity	Improved economic performance for moving seaweed aquaculture into Wind Farm (van den Burg et al., 2016) and reducing biomass waste streams (Balina et al., 2017).
Net/ negative carbon emission potential	Contributing to Net Zero policies set by governments (Fuss et al., 2020; International Energy Agency, 2021)
Simple and efficient	Meeting principles of Green Chemistry (Clark, 1999)

After defining the system requirements, a baseline design could be made and is achievable using several methodologies, in the case of the seaweed biorefinery design for this analysis, C-K design theory was used owing to the conceptual nature of the biorefinery system and innovation potential of the methodology (Cardin et al., 2015; Vourc'h et al., 2018). The use of C-K design methodology involved continual exploration of the concept and knowledge spaces throughout this analysis (Vourc'h et al., 2018). The concept in this instance, is defined as a seaweed biorefinery and knowledge space, included published literature (peer and non-peer reviewed) in addition to expertise of stakeholders in academic and industrial institutions surrounding technical and economic factors of seaweed biorefinery. Information on technologies and techniques relating to seaweed biorefinery were reviewed against the system requirements (Table 10) to validate their applicability and propose a conceptual process system for this TEA (Vourc'h et al., 2018). Literature scoping was performed throughout the study searching for key terms related at each stage of the biorefinery concept. Additionally, unstructured consultation- akin to *The Bioeconomist* approach where individuals are active within a given supply chain interacting with key stakeholders (Lask et al., 2017) – was used amongst subject matter experts from chemical and biological engineering, green chemistry, renewable energy, systems engineering and industry professionals working with anaerobic digestion, ensilage, and microwave technologies.

6.2.2. Modelling and Profitability Analysis

Information to simulate the biological, technological, and economic components of the conceptual process system was collected using a general literature review of peer and non-peer reviewed sources including technical reports and websites of technology manufacturers and product distributors. Consultation with technology providers was also used to access technical and commercial information that was not readily available in published form- following the same methodological approach of Van den Burg (2016) owing to equipment and labour costs not readily available in published form. Information provided by business representatives such as Sales personnel, was shared confidentially between the lead investigator (RO) and business professionals (n=3). All calculations for the process simulation and discounted cash flow analysis were done using Microsoft Excel. The process assessment involved parameterising the biological and technological aspects of the conceptual process system using values drawn

from relevant literature on a specific component such as seaweed growth rate per metre of line, moisture content of sugar kelp, mass balance and so on (Dave et al., 2013) and simulating-based on user defined values benchmarked from literature- to explore the technical dimension of the system prior to profitability analysis.

Process simulation

The seaweed yield potential defined as the total of fresh mass (FM) in kilograms (kg) that would supply seaweed biomass to a nearby processing facility was first estimated. Estimate the seaweed yield of farm was performed first to determine the requirements of equipment size in downstream processing i.e. seaweed biorefinery (Nazemi et al., 2021). The seaweed farm was based on the typical nearshore farming method called the “longline technique” involving anchors, buoys, and rope lines for maintaining the structure and cultivating the seaweed biomass (**Figure 27**).

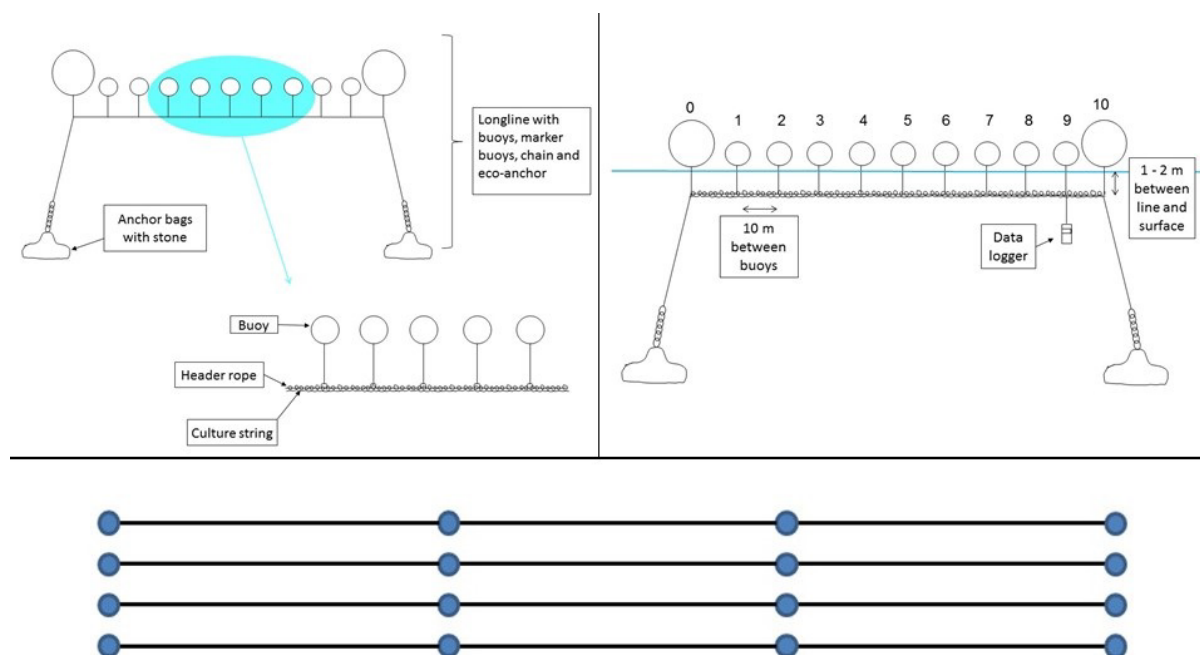


Figure 27- Schematic of seaweed farm module using “long line technique”- figure extracted directly, with no edits from Edwards et al., (2016). Top images present horizontal view of module and bottom illustrates birds eye perspective.

An individual module was parameterised with the values shown in Table 11. The module parameter values were extracted from the protocol on seaweed farming developed as part of the EnAlgae project which illustrates the most common practices employed in the sector (Edwards et al., 2016).

Table 11- Parameters and values of individual module extracted from Edwards et al., (2016) and used to simulate seaweed farm for techno-economic assessment.

Parameters of Seaweed Farm Module	Value
Culture line length (m)	280
Number of culture lines	3
Total available culture line (m)	840
Distance between culture lines (m)	10
Farm width (m)	20
Anchor points	4
Footprint of module (m ²)	5600

Seaweed production was calculated as a function of total culture line (TCL) per module multiplied by the total number of modules (TM) and fresh biomass per metre of line (FM m) (Equation 1)

$$\text{Farm Yield} = (\text{TCL} * \text{TM}) * \text{FM per m}$$

Equation 1- Formulae for estimating Seaweed Farm Yield in TEA simulations.

The value of final fresh seaweed biomass per metre of line (FM Kg m) was user defined as growth rates can vary by region and isn't necessarily standardised as shown in Van Der Molen (2018). For this TEA, a value of 13.65kg per m of culture line was used as a starting point, representing the mid-point value of seaweed production from farm simulations around the UK by Van Der Molen (2018). The module was multiplied to estimate a farm's production capacity based on a set scale of kilometre squared (km²). For this assessment, a farm size of 0.25 km² was used owing to recommendations of a local seaweed enterprise (n=1) and is the largest UK farm license granted to date (HM Government, 2022). After estimating the yield of biomass from a seaweed farm, the mass of chemical compounds in the seaweed was calculated using the total volume of biomass supplied from a farm and divided into chemical composition of sugar kelp organisms including sugars (%) and proteins (%). The % values used for target sugars in this assessment are summarised in Table 12 in addition to the reference sources.

Table 12- Seaweed chemical composition parameters and values used for techno-economic assessment.

Parameters of Seaweed Composition	Input Value	Data Source
Dry Mass content of seaweed (% FW)	10	Schiener et al., (2015)
Total sugar/ Carbohydrate Content (% of Kg DM)	75	Schiener et al., (2015)
Total Alginate (% of Kg DM)	28.5	Schiener et al., (2015)
Total Mannitol (% of Kg DM)	24	Schiener et al., (2015)
Total Laminarin (% of Kg DM)	06	Schiener et al., (2015)
Total Cellulose (% of Kg DM)	11	Schiener et al., (2015)
Total Fucoidan (% Kg DM)	06	(Bruhn et al., 2017)
Total Protein (% of Kg DM)	07	(Sharma et al., 2018)
Total Ash content (% of DM)	25	(Sharma et al., 2018)

Core technologies for the biorefinery process were broken into two main phases, firstly, a post-harvest stage (drying and/or cooking seaweed) using continuous Microwave Drying process technology (Radoiu, 2020). This stage is followed by extraction of target chemicals (sodium alginate, fucoidan and Biochar/waste sugar-protein feedstock) using a Microwave Reactor operating in continuous mode (Priecel & Lopez-Sanchez, 2019) (**Figure 28**).

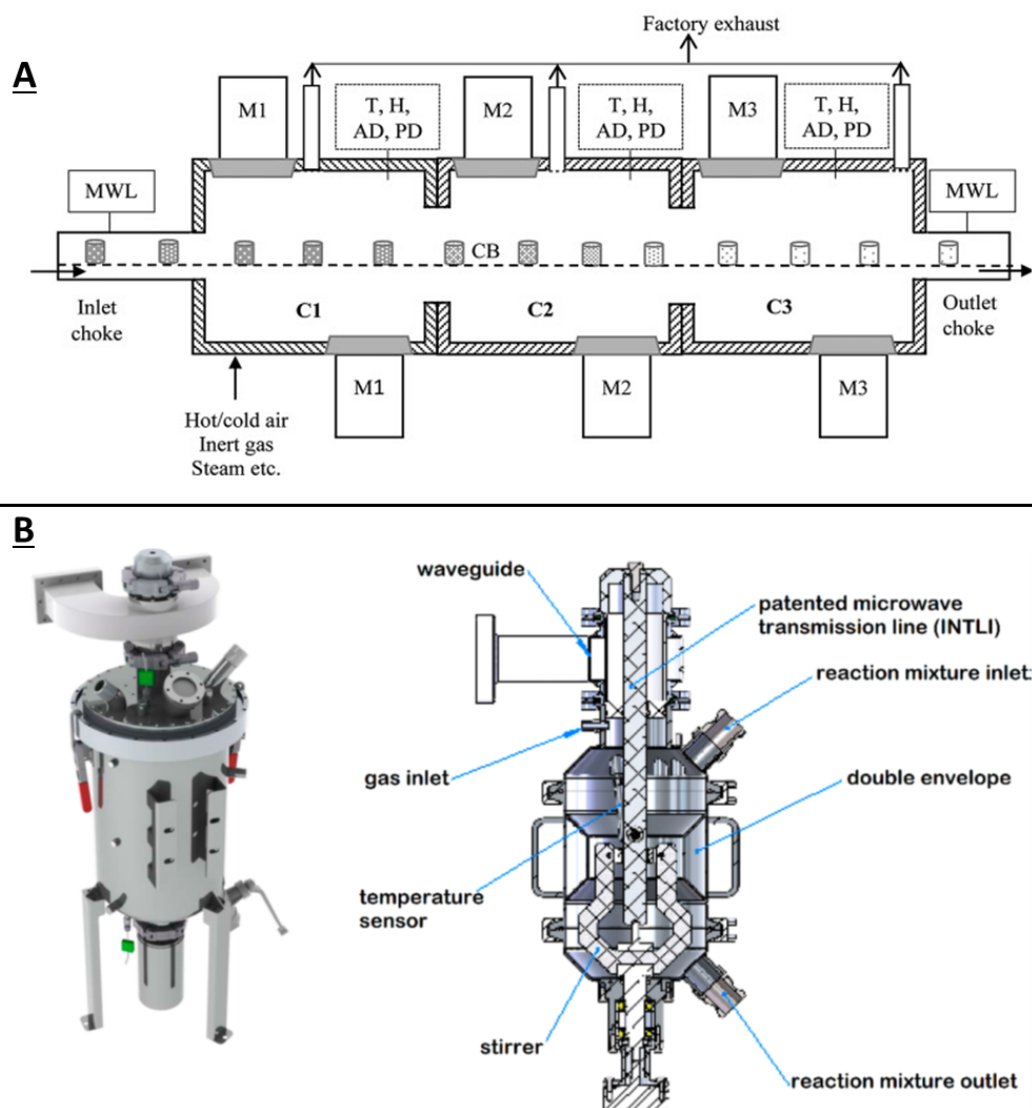


Figure 28- A) Schematic of a continuous tunnel microwave dryer with 3 multimode cavities taken from Radoiu (2020)- PD= product detector, MWL= microwave leakage detector; CB= conveyor belt; C1, C2, C3 – microwave cavities. B) Image (left) and schematic (right) cross section of Sairem 20L Microwave Labotron reactor extracted from Priecel & Lopez-Sanchez, (2019) (“copyright SAIREM”) and edited into a single image.

During the harvesting period of seaweed aquaculture, seaweed was assumed to be immediately dried in a microwave unit. The drying phase of the simulation included reduction in the moisture content of the feedstock to <10% to prevent microbial growth and spoilage and thus long-term preservation of the biomass or supply of whole dried biomass for food market applications (Zambrano et al., 2019). The evaporation rate for 1kg of water from the feedstock

was assumed as 1 kilowatt of power for 1 hour based on existing drying kinetics of the technology (SAIREM, 2020). The standard microwave unit used in the simulation has a power capacity of 16kw microwave energy but was scaled up to meet the required processing capacity based on farming yields. The final energy demand of using the microwave energy tunnel for drying a feedstock was calculated based on the total energy required for drying the feedstock (1 kWh/ kg water) + 20% to account for added energy needed for operating the unit and conversion efficiencies- recommended by product manufacturer (n=1). Subsequently, microwave assisted extraction of target chemical compounds was modelled using the parameters outlined in Table 12 based on values from literature. A standard microwave reactor with a 6kw power capacity and 20 litre (L) working volume was the basis of the scaled unit (n=1) (Priel & Lopez-Sanchez, 2019).

Economic evaluation

A Discounted Cash Flow (DCF) analysis was used to evaluate profitability potential of the seaweed biorefinery component of the conceptual process system (**Figure 29**). To conduct DCF, the Net Present Value formula, a common calculation for financial valuations (Cardin, 2014; Žižlavský, 2014), was used for this assessment and is shown in Equation 2. A project is considered profitable if over the lifecycle of the project and given a certain rate of interest/discount, a positive NPV (£) is calculated (Cardin et al., 2015; Garrett, 2013).

$$NPV = \sum_{i=1}^n \frac{\text{Cash Flow} = \text{Revenue} - \text{Cost}}{(1 + r)^i} - \text{Initial Investment}$$

Equation 2- Formula calculating Net Present Value of an operation where i is a given timepoint and r equated to a discount rate in percent.

Cash flow defines the sum of revenue (£) minus the costs (£) of operation defined as Operational Expenditure (OpEx) at a given timepoint (day/month/years). OpEx contains both Fixed costs such as personnel, overhead & maintenance, quality and assurance, insurance and taxes, and Variable costs such as price of feedstock, electricity, and cost of sales (Farooq et al.,

2020; Zhang & Thomsen, 2021). Initial investment is considered the starting Capital Expenditure (CapEx) that includes such things as direct costs of equipment, the indirect costs such as building, side developments and additional piping and lastly, working capital covering start-up and permits in addition to project contingency for a processing plant (Buchner et al., 2018; Farooq et al., 2020). CapEx and OpEx factors used for guiding cost estimations in this study are summarised in Table 13. The discount factor/ rate is used to apply a rate of interest (%), typically based market interest rate, for sourcing the initial investment and/or account for inflationary pressures such as the increases to consumable prices needed as part of OpEx (Emmerling et al., 2019; Sadhukhan Jhuma et al., 2014).

Table 13- Capital and Operation cost factors for pilot process developments taken from (Farooq et al., 2020)

Capital Costs (CapEx)	Operating Costs (OpEx)
Direct capital costs - Equipment	Fixed operating costs - Personnel - Quality and Assurance - Overhead & maintenance - Insurance and taxes
Indirect Capital Costs - Buildings - Side Developments - Additional piping	Variable operating costs - Feedstock - Electricity - Marketing
Working Capital - Start-up and permits - Project contingency	

A price assumption was used for calculating the cost of feedstock supplied from a nearby seaweed farm. The unit price of £0.50-1.00 per kilogram of fresh seaweed was based on sale prices provided in a Crown Estates seaweed economic feasibility report (Menzies et al., 2021) and assumed to cover the costs of production based on current commercially viable operations setting these price points. To estimate the CapEx of a microwave facility, the direct equipment

costs was first calculated. Prices were provided for the standard microwave drying unit (16kw capacity) and microwave reactor (6kw capacity) by a technology manufacturer (n=1) and converted from Euros to Great British Pound (GBP) with an exchange rate of 1 Euro:0.87 GBP. Next, the equipment price for units beyond the standard scales of 16kw (drying) and 6kw (reaction) were calculated using the “rule of six tenths”, an economic rule whereby approximate costs can be obtained if the cost of a similar item of different size or capacity is known (Equation 3) (Rosario et al., 2017; Tribe & Alpine, 1986).

$$C_b = C_a \left(\frac{S_b}{S_a} \right)^{0.6}$$

Equation 3- Rule of six tenths for calculating manufacturing costs of comparable technologies of different scale.

Where C_B is the approximate cost (£) of equipment having size S_B , C_A is the known cost (£) of equipment having corresponding size S_A (same units as S_B), and S_B/S_A is the ratio known as the size factor corresponding to equipment of focus. The final unit price of the microwave equipment at scale was then used to calculate remaining CapEx. To that end, cost parameters and values were taken from similar techno-economic analyses of microwave biorefinery processes (Nguyen & Zhang, 2020; Zhang & Thomsen, 2021) and are summarised in Table 14 alongside the OpEx for both the microwave drying stage and microwave aided chemical extraction.

Table 14- Direct Fixed Capital (DFC) estimations calculated by SuperPro default settings extracted from *Nguyen & Zhang (2020)* and *Zhang & Thomsen (2021)* for microwave aided biorefinery TEA analyses of shellfish waste and macroalgae

- TPDC= Total Plant Direct Costs

-TPIC= Total Plant Indirect Cost

-CFC= Contractor's Feed & Contingency

$$\text{DFC} = \text{TPDC} + \text{TPIC} + \text{CFC}$$

TPDC	=	(1) + (2) + (3) + (4) + (5) + (6) + (7) + (8) + (9)	
	(1)	Equipment purchase cost (PC, Listed & Unlisted PC)	LPC + UPC
	(2)	Installation for Listed & Unlisted Equipment	ILE + IUE
	(3)	Process piping	0.35*PC
	(4)	Instrumentation	0.4*PC
	(5)	Insulation	0.03*PC
	(6)	Electrical	0.10*PC
	(7)	Buildings	0.45*PC
	(8)	Yard improvement	0.15*PC
	(9)	Auxiliary facilities	0.4*PC
TPIC	=	(10) + (11)	
	(10)	Engineering	0.25*TPDC
	(11)	Construction	0.35*TPDC
CFC	=	(12) + (13)	
	(12)	Contractor's fee	0.05*(TPDC + TPIC)
	(13)	Contingency	0.1*(TPDC + TPIC)
OpEx = FOC + VOC			
FOC	=	(14) + (15) + (16) + (17) + (18) + (19) + (20)	
	(14)	Labour & Supervision (LS)	0.016*DCF
	(15)	Quality and Assurance	0.15*LS
	(16)	Insurance Taxes	0.07*DCF
	(17)	Building Maintenance	-

VOC	(18)	Feedstock supply price (FSP)	Price per kg of fresh seaweed
	(19)	Feedstock supply costs	Farm yield* FSP
	(20)	Electricity costs	User defined
	(21)	Marketing	Total revenue*0.1

Revenue estimations were made using the total units of product potentials created during the stages of microwave processing- cooking and chemical extraction- based on the market retail pricing of similar products on distributor websites³ and/or sale prices recorded in the Crown Estate’s seaweed economic feasibility report (Menzies et al., 2021). Remaining assumptions arising during the calculation of final process outputs including calculation of biorefinery run time, electricity costs of operation, mass transfer efficiency of the process and cost of deionised water supply, can be found in Table 24. Owing to the uncertainty within the process system including revenue potentials given varying sale prices of products discovered in addition to performance of the equipment in operation, a sensitivity analysis was applied, testing how change in variables alters final outputs such as NPV (Farooq et al., 2020; Nguyen & Zhang, 2020). The sensitivity analysis used the highest and lowest values sourced during the evidence review to further explore economic characteristics in face of performance uncertainty.

6.3.Results

6.3.1. Bioprocess- Conceptual Baseline Design

Unstructured consultation with relevant parties (n=10) from green chemistry, seaweed biorefinery technology and biological engineering and literature review of seaweed processing (pre-treatment and value extraction techniques) resulted in a proposed clean power-microwave aided seaweed process (CMSP) system (**Figure 29**). The conceptual industrial process for extracting value from seaweed starts with a production stage of open-sea seaweed aquaculture for procurement of macroalgal feedstock (Edwards et al., 2016). Following harvest of fresh

³ See Table 24 in appendix and TEA model in supplementary materials for links and screen grabs of distributors used during the profitability analysis.

seaweed, a microwave “pre-treatment” is used to remove moisture content and preserve the biomass for further value extraction and/or access to the first product potentials i.e. dried/ cooked seaweed (Akomea-Frempong et al., 2021; Cherry et al., 2019). Microwave pre-treatment was selected owing to the ability scale-up operations (Radoiu, 2020); known process kinetics of energy and mass transfer (Badmus et al., 2019); readily available technology (Priecel & Lopez-Sanchez, 2019; SAIREM, 2020); significantly efficient energy transfer and drying time (Santhoshkumar et al., 2023) and integration potential with clean power to utilise excess/ wasted potential and low-to-zero carbon emission potential (González-Garay et al., 2021; Goyal, 2022). Alternative seaweed pre-treatment techniques considered included oven and open-air drying, ensilage (optimised and non), freezing and fermentation but were considered did not meet system requirements to the extent of microwaves during the time of review.

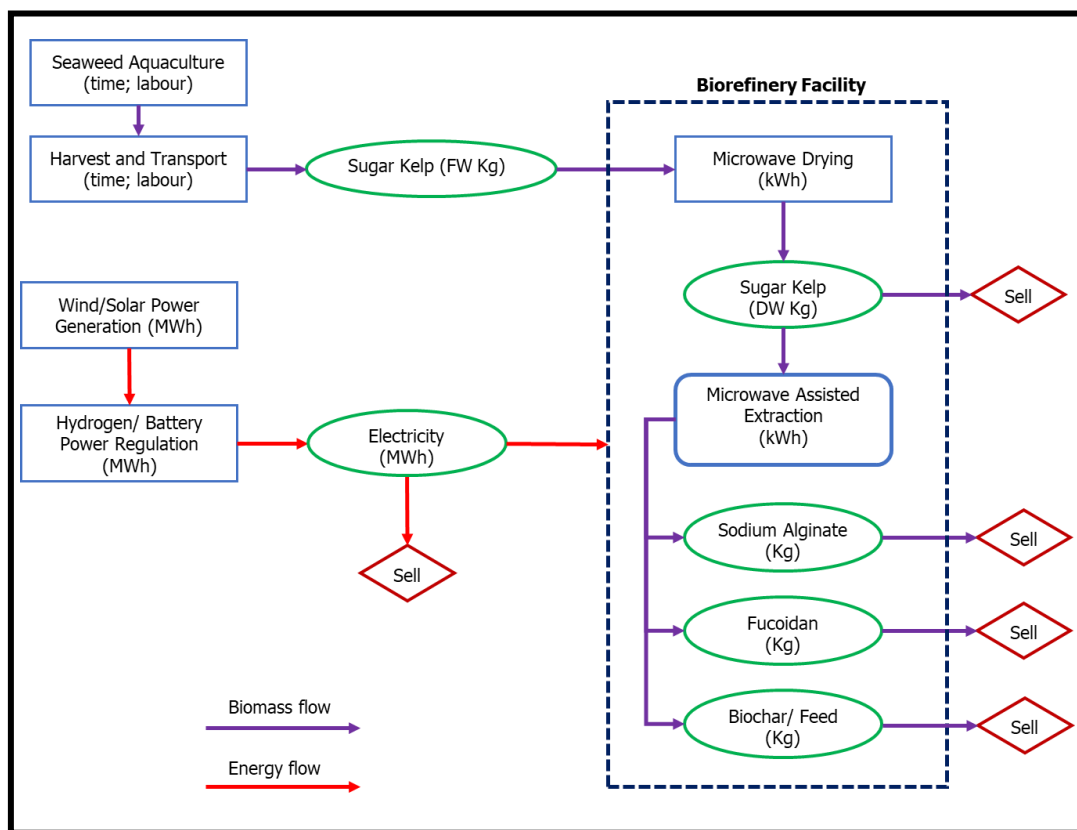


Figure 29- Clean power Microwave biorefinery process system for value extraction from sugar kelp biomass

The microwave drying stage can be followed by a microwave assisted extraction step to extract sodium alginate, fucoidan and biochar/feed products from dried seaweed for further market retail potential. The target compounds (sodium alginate and fucoidan) were selected owing to the commodities reaching the most valuable market applications namely, pharmaceutical grade retail, and existing market demand (Balina et al., 2017; Rhein-Knudsen & Meyer, 2021; Wijesinghe & Jeon, 2012) in addition to proven extraction methods for sodium alginate, fucoidan and biochar/animal feed in closely related seaweed species (Yuan & Macquarrie, 2015).

Lastly, owing to the system requirements of low-to-zero carbon emissions within seaweed processing (Table 10), clean power technologies were integrated with the seaweed biorefinery (**Figure 29**). The source of electricity to power the microwave facility is assumed to come from clean power technologies, namely, wind turbine and solar photovoltaic (PV) farms including utilisation of wasted electricity potential⁴. The intermittency of energy production from wind and solar technologies necessitates additional units for power regulation and security (**Figure 29**) (Aktaş, 2021). Combined hydrogen and battery equipment was selected as part of the process system to create reliable flow of energy from wind and solar power infrastructure into the seaweed biorefinery facility. A hydrogen-battery unit was also selected for further assumed benefits including meeting the system requirement of scalable capacity; relatively higher energy efficiency from production-to-use (%) and greater net energy potential over the lifecycle of projects compared with using individual (battery or hydrogen) components (Pellow et al., 2015).

6.3.2. Techno-Economic Assessment

The techno-economic assessment resulted in the following: estimated production potential (biomass yield and biochemical totals) and costs of a 0.25km² seaweed farm; the capacity requirements, estimated costs and NPV of a connected microwave drying-only system; and capacity requirements, estimated costs and NPV of a microwave assisted extraction process with target commodities of sodium alginate, fucoidan and animal feed. See excel file in

⁴ Curtailment of UK wind power equated to 5.8 TWh in 2020-2021 incur significant financial costs (Lane Clark & Peacock LLP, 2022)

supplementary materials “TEA model” for all calculations, process simulations and economic assumptions used during exploration of economic characteristics of the system.

Seaweed Farming

The first stage of the TEA was to estimate the production potential of a 0.25 km² sugar kelp farm to calculate commodities potential, supply costs and facilitate the design of a coupled downstream biorefinery based on seaweed farm specifications/ outputs. All parameters of farming inputs and outputs including the annual seaweed biomass harvested, volumes of available target chemicals and costs of the production, are shown in Table 15 and Table 16. The farm yield was calculated using an expected growth rate of 13 kg per metre of line resulting in 163800 kg seaweed (FM) (Table 15). The total cost of supplying the feedstock was estimated at £122850, based on a fixed, mid-point market price of £0.75 per kg of fresh seaweed and thus assumed to cover the costs of production.

Table 15- Summary of seaweed farm inputs and outputs used for estimating production performance and sizing requirements of microwave-aided processing facility downstream of farm.

Seaweed Farm	Unit	Seaweed Farm Outputs	Unit
Number of Modules (nearshore longline)	36	Biomass Yield (kg FM per year)	163800
FM per metre line (kg)	13	Biomass Yield (kg DM kg per year)	16380
Onsite deployment (date, dd/mm/yyyy)	01/10/2022	Farm Surface Footprint (m ²)	252000
Harvest day of year (date, dd/mm/yyyy)	02/06/2023	Farm Surface Footprint (km ²)	0.252
Total days of farming	244	Total no. of Anchor points	180
Seaweed Growth Rate_Linear (kg per day)	0.053	Culture lines total length (m)	12600
Harvest Period (days)	90	Total cost of supply (£)	122850
Fixed supply price (£ per kg)	0.75		

The total amount of target compounds were also calculated, including: 12366.90 kg (dm) for sugar content divided into 4668.30 kg (dm) of alginate; 3931.20 kg (dm) of mannitol; 982.80 kg (dm) of laminarin; 1801.80 kg (dm) of cellulose; 982.80 kg (dm) of fucoidan and 1162.98 kg (dm) for protein concentration (Table 16). Further compounds considered important to the TEA for non-financial purposes including product safety and optimisation critique, included polyphenols equating to 111.38 kg (dm); ash content kg (dm) and nitrogen totalling 1474.2 kg (dm).

Table 16- Estimate quantities of target biochemical compounds (sugars, protein, nutrient, and non-combustibles) and moisture content available in the sugar kelp feedstock from a 0.2 km² seaweed farm per annum.

Total chemical composition of feedstock	Unit
Moisture content (kg)	147420
Sugar Content (kg DM)	12366.90
Alginate (kg DM)	4668.30
Mannitol (kg DM)	3931.20
Laminarin (kg DM)	982.80
Cellulose (kg DM)	1801.80
Fucoidan (kg DM)	982.80
Protein (kg DM)	1162.98
Polyphenol content (kg DM)	111.38
Ash content (kg DM)	4422.60
Nitrogen content (kg DM)	1474.2

Microwave Stage 1 (drying only)

Following the estimations of a 0.25km² sugar kelp farm, the capacity requirements of the downstream biorefinery were calculated, starting with the microwave drying system. To remove excess moisture from the feedstock procured from the 0.25km² farm, a microwave drying system with power capacity of 68 Kw was assumed, based on a run time of 2160 hours to match the harvesting rate of the farm (Table 17) and preventing crop decomposition (dried to <10% moisture content within 72 hours of harvest) (Zambrano et al., 2019; del Olmo et al., 2020). The resulting feedstock equated to 16380 kg dm sugar kelp per annum. The energy demand of the microwave drying process was estimated at 176904 kwh, accounting for additional 20% energy demand to run equipment. Next the revenue potential per year was calculated assuming sale of all dried biomass with a price point of £40.42 kg equating to £662079.6 per annum. After revenue calculations, the total direct capital costs were calculated to £3027274.91 and the included operating costs (electricity demand, labour, feedstock costs,

quality and assurance, and marketing) were estimated at £488052.04 with a full breakdown of each cost component shown further in Table 17.

Table 17- Breakdown of microwave drying components including capacity, energy demand and run time in addition to capital cost estimates.

Microwave Unit capacity and costs	Values
Microwave Power Capacity (kw per unit)	68.3
Power used per 1kg water removed (kwh)	1.20
Run time (hours)	2160
Evaporation potential (kg)	147420
Processing capacity (kg dm Biomass)	16380
Energy demand of drying (kwh)	176904
Equipment Direct Purchase Cost (£)	457016.14
Unlisted Purchase Cost (£)	114254.03
Equipment Cost total (£)	571270.17
Total Plant Direct Costs (£)	1645258.10
Total Plant indirect costs	987154.86
Contractor's Fees and Contingency (£)	394861.94
<i>Direct Fixed Capital (£)</i>	3027274.91
Labour and Supervision (£)	48436.40
Quality and Assurance (£)	7265.46
Feedstock supply cost (£)	122850
Electricity costs of microwave drying (£)	26199.48
Electricity assumed for general business (£)	5183.5
Insurance and Taxes (£)	211909.24
Marketing (£)	66207.96
<i>Total Operating Cost (£)</i>	488052.04
Selling price per kg (£)	40.42
Revenue potential per year (£)	662079.6

A sensitivity analysis of the microwave drying process was conducted to explore the changes in operating costs and revenue potential in relation to the variability found at the seaweed

production stage, namely, biomass yield per metre line of seaweed farm (1.2-26.1 kg biomass fm) and feedstock costs per kg (£0.50-1.00), and the market retail value i.e. selling price per kg of dried seaweed (£1-79.83 kg), per annum. The full results of the microwave drying sensitivity are shown in **Figure 30** and **Figure 31**. A breakdown of average costs over a 20 point range are shown in Table 18 with operating costs reducing to £406152.04 and increasing to £692802.04 from a £ 511306.20 mid-point- based on change in total feedstock purchased and at the varying selling price (£1-79.83 kg). Change in revenue potential was discovered to range from a low point of £ 8190.00 to a maximum of £2615230.80, from the mid-point of £760232.10 (Table 18) owing to changing selling price and available biomass processed per annum.

		Biomass processed per season (wet Kg)																			
Price per wet kg (£)		81900	94831.58	107763.158	120694.7368	133626.316	146557.895	159489.5	172421.1	185352.6	198284.2105	211215.8	224147.4	237078.9	250010.5	262942.1	275873.7	288805.3	301736.8	314668.4	327600
	0.5	40950	47415.79	53881.5789	60347.36842	66813.1579	73278.9474	79744.74	86210.53	92676.32	99142.10526	105607.9	112073.7	118539.5	125005.3	131471.1	137936.8	144402.6	150868.4	157334.2	163800
	0.53	43105.3	49911.36	56717.4515	63523.54571	70329.6399	77135.7341	83941.83	90747.92	97554.02	104360.1108	111166.2	117972.3	124778.4	131584.5	138390.6	145196.7	152002.8	158808.9	165615	172421.1
	0.55	45260.5	52406.93	59553.3241	66699.72299	73846.1219	80992.5208	88138.92	95285.32	102431.7	109578.1163	116724.5	123870.9	131017.3	138163.7	145310.1	152456.5	159602.9	166749.3	173895.7	181042.1
	0.58	47415.8	54902.49	62389.1967	69875.90028	77362.6039	84849.3075	92336.01	99822.71	107309.4	114796.1219	122282.8	129769.5	137256.2	144742.9	152229.6	159716.3	167203	174689.8	182176.5	189663.2
	0.61	49571.1	57398.06	65225.0693	73052.07756	80879.0859	88706.0942	96533.1	104360.1	112187.1	120014.1274	127841.1	135668.1	143495.2	151322.2	159149.2	166976.2	174803.2	182630.2	190457.2	198284.2
	0.63	51726.3	59893.63	68060.9418	76228.25485	84395.5679	92562.8809	100730.2	108897.5	117064.8	125232.133	133399.4	141566.8	149734.1	157901.4	166068.7	174236	182403.3	190570.6	198738	206905.3
	0.66	53881.6	62389.2	70896.8144	79404.43213	87912.0499	96419.6676	104927.3	113434.9	121942.5	130450.1385	138957.8	147465.4	155973	164480.6	172988.2	181495.8	190003.5	198511.1	207018.7	215526.3
	0.68	56036.8	64884.76	73732.687	82580.60942	91428.5319	100276.454	109124.4	117972.3	126820.2	135668.144	144516.1	153364	162211.9	171059.8	179907.8	188755.7	197603.6	206451.5	215299.4	224147.4
	0.71	58192.1	67380.33	76568.5596	85756.7867	94945.0139	104133.241	113321.5	122509.7	131697.9	140886.1496	150074.4	159262.6	168450.8	177639.1	186827.3	196015.5	205203.7	214392	223580.2	232768.4
	0.74	60347.4	69875.9	79404.4321	88932.96399	98461.4958	107990.028	117518.6	127047.1	136575.6	146104.1551	155632.7	165161.2	174689.8	184218.3	193746.8	203275.3	212803.9	222332.4	231860.9	241389.5
	0.76	62502.6	72371.47	82240.3047	92109.14127	101977.978	111846.814	121715.7	131584.5	141453.3	151322.1607	161191	171059.8	180928.7	190797.5	200666.3	210535.2	220404	230272.9	240141.7	250010.5
	0.79	64657.9	74867.04	85076.1773	95285.31856	105494.46	115703.601	125912.7	136121.9	146331	156540.1662	166749.3	176958.4	187167.6	197376.7	207585.9	217795	228004.2	238213.3	248422.4	258631.6
	0.82	66813.2	77362.6	87912.0499	98461.49584	109010.942	119560.388	130109.8	140659.3	151208.7	161758.1717	172307.6	182857.1	193406.5	203956	214505.4	225054.8	235604.3	246153.7	256703.2	267252.6
	0.84	68968.4	79858.17	90747.9224	101637.6731	112527.424	123417.175	134306.9	145196.7	156086.4	166976.1773	177865.9	188755.7	199645.4	210535.2	221424.9	232314.7	243204.4	254094.2	264983.9	275873.7
	0.87	71123.7	82353.74	93583.795	104813.8504	116043.906	127273.961	138504	149734.1	160964.1	172194.1828	183424.2	194654.3	205884.3	217114.4	228344.5	239574.5	250804.6	262034.6	273264.7	284494.7
	0.89	73278.9	84849.31	96419.6676	107990.0277	119560.388	131130.748	142701.1	154271.5	165841.8	177412.1884	188982.5	200552.9	212123.3	223693.6	235264	246834.3	258404.7	269975.1	281545.4	293115.8
	0.92	75434.2	87344.88	99255.5402	111166.205	123076.87	134987.535	146898.2	158808.9	170719.5	182630.1939	194540.9	206451.5	218362.2	230272.9	242183.5	254094.2	266004.8	277915.5	289826.2	301736.8
	0.95	77589.5	89840.44	102091.413	114342.3823	126593.352	138844.321	151095.3	163346.3	175597.2	187848.1994	200099.2	212350.1	224601.1	236852.1	249103	261354	273605	285856	298106.9	310357.9
	0.97	79744.7	92336.01	104927.285	117518.5596	130109.834	142701.108	155292.4	167883.7	180474.9	193066.205	205657.5	218248.8	230840	243431.3	256022.6	268613.9	281205.1	293796.4	306387.7	318978.9
	1.00	81900	94831.58	107763.158	120694.7368	133626.316	146557.895	159489.5	172421.1	185352.6	198284.2105	211215.8	224147.4	237078.9	250010.5	262942.1	275873.7	288805.3	301736.8	314668.4	327600

Figure 30- Heat map of change in operating cost for microwave drying process based on varying feedstock price per wet kg and amount of biomass process per season based on varying seaweed production potential per metre of culture line.

Selling Price (£ per kg)	Dried biomass per season (kg)																				
	8190	9483	10776	12069	13363	14656	15949	17242	18535	19828	21122	22415	23708	25001	26294	27587	28881	30174	31467	32760	
	1.00	8190.00	9483.16	10776.32	12069.47	13362.63	14655.79	15948.95	17242.11	18535.26	19828.42	21121.58	22414.74	23707.89	25001.05	26294.21	27587.37	28880.53	30173.68	31466.84	32760.00
	5.15	42169.88	48828.28	55486.68	62145.08	68803.49	75461.89	82120.29	88778.69	95437.09	102095.50	108753.90	115412.30	122070.70	128729.10	135387.51	142045.91	148704.31	155362.71	162021.11	168679.52
	9.30	76149.76	88173.40	100197.05	112220.70	124244.34	136267.99	148291.63	160315.28	172338.93	184362.57	196386.22	208409.86	220433.51	232457.16	244480.80	256504.45	268528.09	280551.74	292575.39	304599.03
	13.45	110129.64	127518.53	144907.42	162296.31	179685.20	197074.09	214462.98	231851.87	249240.76	266629.65	284018.54	301407.43	318796.32	336185.21	353574.10	370962.99	388351.88	405740.77	423129.66	440518.55
	17.60	144109.52	166863.65	189617.78	212371.92	235126.05	257880.19	280634.32	303388.45	326142.59	348896.72	371650.86	394404.99	417159.12	439913.26	462667.39	485421.53	508175.66	530929.80	553683.93	576438.06
	21.74	178089.39	206208.77	234328.15	262447.53	290566.91	318686.29	346805.66	374925.04	403044.42	431163.80	459283.18	487402.55	515521.93	543641.31	571760.69	599880.07	627999.44	656118.82	684238.20	712357.58
	25.89	212069.27	245553.90	279038.52	312523.14	346007.76	379492.38	412977.01	446461.63	479946.25	513430.87	546915.50	580400.12	613884.74	647369.36	680853.98	714338.61	747823.23	781307.85	814792.47	848277.09
	30.04	246049.15	284899.02	323748.89	362598.75	401448.62	440298.48	479148.35	517998.22	556848.08	595697.95	634547.81	673397.68	712247.55	751097.41	789947.28	828797.15	867647.01	906496.88	945346.74	984196.61
	34.19	280029.03	324244.14	368459.25	412674.36	456889.47	501104.58	545319.69	589534.80	633749.91	677965.02	722180.13	766395.24	810610.35	854825.46	899040.58	943255.69	987470.80	1031685.91	1075901.02	1120116.13
	38.34	314008.91	363589.26	413169.62	462749.97	512330.33	561910.68	611491.04	661071.39	710651.74	760232.10	809812.45	859392.81	908973.16	958553.52	1008133.87	1057714.22	1107294.58	1156874.93	1206455.29	1256035.64
	42.49	347988.79	402934.39	457879.99	512825.58	567771.18	622716.78	677662.38	732607.98	787553.58	842499.17	897444.77	952390.37	1007335.97	1062281.57	1117227.17	1172172.76	1227118.36	1282063.96	1337009.56	1391955.16
	46.64	381968.67	442279.51	502590.35	562901.20	623212.04	683522.88	743833.72	804144.57	864455.41	924766.25	985077.09	1045387.93	1105698.78	1166009.62	1226320.46	1286631.30	1346942.15	1407252.99	1467563.83	1527874.67
	50.79	415948.55	481624.63	547300.72	612976.81	678652.89	744328.98	810005.07	875681.15	941357.24	1007033.33	1072709.41	1138385.50	1204061.58	1269737.67	1335413.76	1401089.84	1466765.93	1532442.02	1598118.10	1663794.19
	54.94	449928.43	520969.76	592011.09	663052.42	734093.75	805135.08	876176.41	947217.74	1018259.07	1089300.40	1160341.73	1231383.06	1302424.39	1373465.72	1444507.05	1515548.38	1586589.71	1657631.04	1728672.37	1799713.71
	59.09	483908.31	560314.88	636721.45	713128.03	789534.60	865941.18	942347.75	1018754.33	1095160.90	1171567.48	1247974.05	1324380.62	1400787.20	1477193.77	1553600.35	1630006.92	1706413.50	1782820.07	1859226.65	1935633.22
	63.23	517888.18	599660.00	681431.82	763203.64	844975.46	926747.28	1008519.10	1090290.91	1172062.73	1253834.55	1335606.37	1417378.19	1499150.01	1580921.83	1662693.64	1744465.46	1826237.28	1908009.10	1989780.92	2071552.74
	67.38	551868.06	639005.13	726142.19	813279.25	900416.31	987553.38	1074690.44	1161827.50	1248964.56	1336101.63	1423238.69	1510375.75	1597512.81	1684649.88	1771786.94	1858924.00	1946061.06	2033198.13	2120335.19	2207472.25
	71.53	585847.94	678350.25	770852.56	863354.86	955857.17	1048359.48	1140861.78	1233364.09	1325866.40	1418368.70	1510871.01	1603373.32	1695875.62	1788377.93	1880880.24	1973382.54	2065884.85	2158387.16	2250889.46	2343391.77
	75.68	619827.82	717695.37	815562.92	913430.47	1011298.02	1109165.57	1207033.13	1304900.68	1402768.23	1500635.78	1598503.33	1696370.88	1794238.43	1892105.98	1989973.53	2087841.08	2185708.63	2283576.18	2381443.73	2479311.28
79.83	653807.70	757040.49	860273.29	963506.08	1066738.88	1169971.67	1273204.47	1376437.26	1479670.06	1582902.85	1686135.65	1789368.44	1892601.24	1995834.03	2099066.83	2202299.62	2305532.42	2408765.21	2511998.01	2615230.80	

Figure 31- Heat map of change in revenue potential per annum for microwave drying process based on varying selling price per kg of dried material and amount of biomass process per season based on varying seaweed production potential per metre of culture line.

Table 18- Average cost and revenue potential range based on microwave drying process sensitivity.

<i>Rank (low to high)</i>	Cost potential (£)	Revenue potential (£)
<i>1</i>	406152.04	8190.00
<i>2</i>	415113.40	48828.28
<i>3</i>	424755.37	100197.05
<i>4</i>	435077.94	162296.31
<i>5</i>	446081.13	235126.05
<i>6</i>	457764.93	318686.29
<i>7</i>	470129.33	412977.01
<i>8</i>	483174.34	517998.22
<i>9</i>	496899.97	633749.91
<i>10</i>	511306.20	760232.10
<i>11</i>	526393.04	897444.77
<i>12</i>	542160.49	1045387.93
<i>13</i>	558608.55	1204061.58
<i>14</i>	575737.22	1373465.72
<i>15</i>	593546.50	1553600.35
<i>16</i>	612036.39	1744465.46
<i>17</i>	631206.89	1946061.06
<i>18</i>	651058.00	2158387.16
<i>19</i>	671589.72	2381443.73
<i>20</i>	692802.04	2615230.80

Net Present Value (NPV) was calculated over an eight-year period to characterise high level economic viability of the microwave drying process-only, before further assessments with the added microwave assisted-biorefinery component (**Figure 29**). NPV was calculated for three scenarios, namely, highest feedstock costs and lowest revenue potential a mid-level cost and revenue generation, and lowest cost, high revenue potential (Table 18). A net profit was achieved and maintained in both the mid-cost, revenue, and low cost, high revenue scenarios. In a high cost and low revenue scenario, net profit was not achievable in the eight-year period of operation with debt of £-319728.27. The highest profitability was found in year two following the offset of direct capital costs in year one (to initiate operations) and peaked at £1824665.90 in the low cost, high revenue scenario (**Figure 32**).

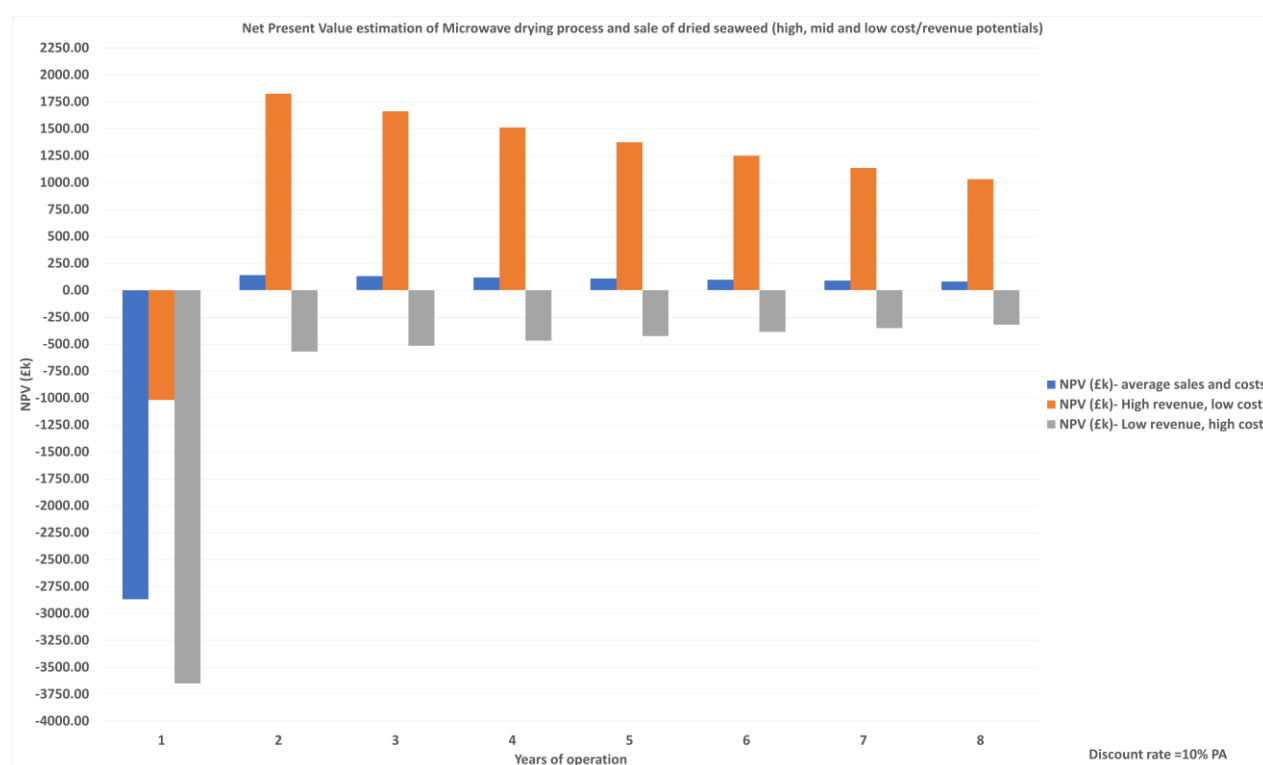


Figure 32- NPV for 3 microwave drying scenarios :average value sales price for dried seaweed and average production costs; High sale price and low production costs and low unit sale price and high production costs.

The next stage of the assessments explored the techno-economic characteristics of the additional microwave-aided biorefinery process following the drying stage of the seaweed feedstock. Table 19 shows all parameters and values used or generated for the biorefinery process simulation. A microwave reactor with a power capacity of 14 kw and 47L working volume was assumed to process approximately half the expected dried biomass per annum- 8125 kg DM (Table 17). The energy demand of the microwave biorefinery was estimated to reach 32323.20 kwh, accounting for additional 20% energy demand to run equipment and 14 kwh power capacity used during operation. Next the revenue potential per year was calculated assuming sale of all three products: sodium alginate and fucoidan with a sale price of £208 kg and remaining biomass sold as biochar at £6.19 kg- reaching a yearly revenue of £254094.58. Total direct capital costs and operating costs inclusive of a £40 kg seaweed supply to offset the costs of the microwave drying stage, were estimated to reach £1341385.73 and £519163.45, respectively.

Table 19- Breakdown of microwave drying components including capacity, energy demand and run time in addition to capital cost estimates.

MICROWAVE UNIT 2 (BIOREFINERY PROCESS)	UNITS
Microwave reactor power capacity (kw)	14
Reactor working volume (L)	47
Biomass loading rate (kg)	4.22
Run time (hours)	1924
Energy demand per run (kwh)	32323.20
Equipment Direct Purchase Cost (£)	202503.88
Unlisted Purchase Cost (£)	50625.97
Equipment Cost total (£)	253129.86
Total Plant Direct Costs (£)	729013.99
Total Plant indirect costs (£)	437408.39
Contractor's Fees and Contingency (£)	174963.36
Direct Fixed Capital (£)	1341385.73
Biomass processed (kg pa)	8125.69
Mass transfer (%)	0.4
DI water demand (L)	81660.97
Sodium Alginate (kg)	9266.33
Furoidan (kg)	195.02
Biomass waste (kg)	7004.35
Total Sugar & Protein content of Biomass Waste (kg DM)	3369.09
Alginate selling price (£ kg)	208
Furoidan selling Price (£ kg)	208
Biochar/feed selling price (£ per sugar/protein kg DM)	6.19
Revenue (£)	254094.58
Total Operating Cost (£)	519163.45

Given uncertainties in the performance of the biorefinery process, namely, mass balance for target compounds/ extraction efficiency (0.1-99%) and the variable selling price of polysaccharide products (£28.33-300+ kg) depending on material grades i.e. food to pharmaceutical, a sensitivity analysis was conducted to measure change in revenue potential per annum. The full results of the microwave biorefinery process sensitivity analysis are shown in **Figure 33** and **Figure 34**. A breakdown of average revenue potentials over a 20-point range are shown in Table 20, with the lowest revenue potential at £50909.46 to a maximum of £864802.05, from the mid-point of £250364.86.

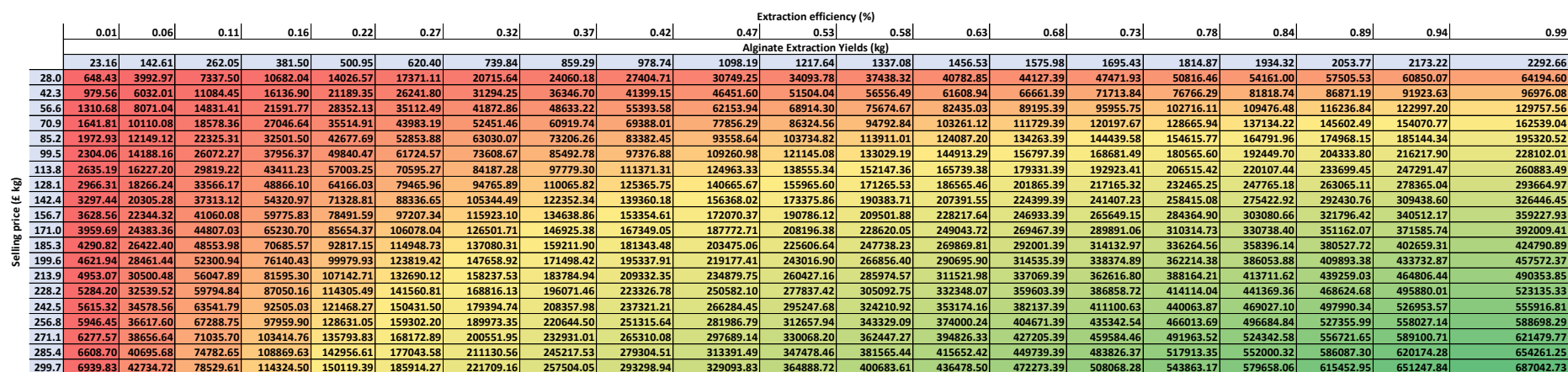


Figure 33- heat map of change in revenue potential for sodium alginate procured from microwave biorefinery process based on varying sale price per kg (£) and extraction efficiency during microwave reaction (%).

Selling price (£/kg)	Extraction efficiency (%)																			
	0.01	0.06	0.11	0.16	0.22	0.27	0.32	0.37	0.42	0.47	0.53	0.58	0.63	0.68	0.73	0.78	0.84	0.89	0.94	0.99
	Fucoidan Extraction Yields (kg)																			
	4.88	30.02	55.17	80.32	105.46	130.61	155.76	180.90	206.05	231.20	256.34	281.49	306.64	331.78	356.93	382.08	407.23	432.37	457.52	482.67
	28.0	136.51	840.62	1544.74	2248.85	2952.96	3657.08	4361.19	5065.30	5769.41	6473.53	7177.64	7881.75	8585.86	9289.98	9994.09	10698.20	11402.32	12106.43	12810.54
42.3	206.22	1269.90	2333.57	3397.24	4460.92	5524.59	6588.26	7651.94	8715.61	9779.28	10842.96	11906.63	12970.30	14033.98	15097.65	16161.32	17225.00	18288.67	19352.34	20416.02
56.6	275.93	1699.17	3122.40	4545.64	5968.87	7392.10	8815.34	10238.57	11661.81	13085.04	14508.27	15931.51	17354.74	18777.98	20201.21	21624.45	23047.68	24470.91	25894.15	27317.38
70.9	345.64	2128.44	3911.23	5694.03	7476.82	9259.62	11042.41	12825.21	14608.00	16390.80	18173.59	19956.39	21739.18	23521.98	25304.77	27087.57	28870.36	30653.16	32435.95	34218.75
85.2	415.35	2557.71	4700.07	6842.42	8984.78	11127.13	13269.49	15411.84	17554.20	19696.55	21838.91	23981.27	26123.62	28265.98	30408.33	32550.69	34693.04	36835.40	38977.75	41120.11
99.5	485.07	2986.98	5488.90	7990.81	10492.73	12994.65	15496.56	17998.48	20500.40	23002.31	25504.23	28006.14	30508.06	33009.98	35511.89	38013.81	40515.73	43017.64	45519.56	48021.47
113.8	554.78	3416.25	6277.73	9139.21	12000.68	14862.16	17723.64	20585.12	23446.59	26308.07	29169.55	32031.02	34892.50	37753.98	40615.45	43476.93	46338.41	49199.89	52061.36	54922.84
128.1	624.49	3845.52	7066.56	10287.60	13508.64	16729.68	19950.71	23171.75	26392.79	29613.83	32834.86	36055.90	39276.94	42497.98	45719.01	48940.05	52161.09	55382.13	58603.17	61824.20
142.4	694.20	4274.80	7855.39	11435.99	15016.59	18597.19	22177.79	25758.39	29338.99	32919.58	36500.18	40080.78	43661.38	47241.98	50822.58	54403.17	57983.77	61564.37	65144.97	68725.57
156.7	763.91	4704.07	8644.23	12584.39	16524.54	20464.70	24404.86	28345.02	32285.18	36225.34	40165.50	44105.66	48045.82	51985.98	55926.14	59866.30	63806.45	67746.61	71686.77	75626.93
171.0	833.62	5133.34	9433.06	13732.78	18032.50	22332.22	26631.94	30931.66	35231.38	39531.10	43830.82	48130.54	52430.26	56729.98	61029.70	65329.42	69629.14	73928.86	78228.58	82528.30
185.3	903.33	5562.61	10221.89	14881.17	19540.45	24199.73	28859.01	33518.29	38177.57	42836.86	47496.14	52155.42	56814.70	61473.98	66133.26	70792.54	75451.82	80111.10	84770.38	89429.66
199.6	973.04	5991.88	11010.72	16029.56	21048.41	26067.25	31086.09	36104.93	41123.77	46142.61	51161.45	56180.29	61199.14	66217.98	71236.82	76255.66	81274.50	86293.34	91312.18	96331.03
213.9	1042.75	6421.15	11799.56	17177.96	22556.36	27934.76	33313.16	38691.57	44069.97	49448.37	54826.77	60205.17	65583.58	70961.98	76340.38	81718.78	87097.18	92475.59	97853.99	103232.39
228.2	1112.46	6850.42	12588.39	18326.35	24064.31	29802.28	35540.24	41278.20	47016.16	52754.13	58492.09	64230.05	69968.01	75705.98	81443.94	87181.90	92919.87	98657.83	104395.79	110133.75
242.5	1182.17	7279.70	13377.22	19474.74	25572.27	31669.79	37767.31	43864.84	49962.36	56059.88	62157.41	68254.93	74352.45	80449.98	86547.50	92645.02	98742.55	104840.07	110937.59	117035.12
256.8	1251.88	7708.97	14166.05	20623.14	27080.22	33537.30	39994.39	46451.47	52908.56	59365.64	65822.73	72279.81	78736.89	85193.98	91651.06	98108.15	104565.23	111022.31	117479.40	123936.48
271.1	1321.59	8138.24	14954.88	21771.53	28588.17	35404.82	42221.46	49038.11	55854.75	62671.40	69488.04	76304.69	83121.33	89937.98	96754.62	103571.27	110387.91	117204.56	124021.20	130837.85
285.4	1391.31	8567.51	15743.72	22919.92	30096.13	37272.33	44448.54	51624.74	58800.95	65977.16	73153.36	80329.57	87505.77	94681.98	101858.18	109034.39	116210.59	123386.80	130563.01	137739.21
299.7	1461.02	8996.78	16532.55	24068.31	31604.08	39139.85	46675.61	54211.38	61747.15	69282.91	76818.68	84354.45	91890.21	99425.98	106961.74	114497.51	122033.28	129569.04	137104.81	144640.58
Waste Yield																				
	8097.66	7953.07	7808.47	7663.88	7519.28	7374.69	7230.09	7085.50	6940.90	6796.31	6651.71	6507.12	6362.52	6217.93	6073.34	5928.74	5784.15	5639.55	5494.96	5350.36
Biochar Revenue Potential (£)																				
	50124.51	49229.47	48334.43	47439.39	46544.35	45649.31	44754.27	43859.23	42964.19	42069.15	41174.11	40279.07	39384.03	38488.99	37593.95	36698.91	35803.87	34908.83	34013.79	33118.75

Figure 34- heat map of change in revenue potential for fucoidan procured from microwave biorefinery process based on varying sale price per kg (£) and extraction efficiency during microwave reaction (%) in addition to change in overall “waste”/ biochar yield owing to changes in extraction efficiency of polysaccharides.

Table 20- Average cost and revenue potential range based on microwave biorefinery process sensitivity.

<i>Rank (low to high)</i>	<i>Revenue potential (£)</i>
1	50909.46
2	56531.37
3	66288.24
4	80180.06
5	98206.82
6	120368.53
7	146665.19
8	177096.80
9	211663.35
10	250364.86
11	293201.31
12	340172.71
13	391279.06
14	446520.36
15	505896.60
16	569407.80
17	637053.94
18	708835.03
19	784751.07
20	864802.05

Net Present Value (NPV) was calculated over an eight-year period to evaluate the preliminary economic viability of the microwave biorefinery stage within the conceptual process (**Figure 29**). Using a 10% discount rate, NPV was calculated for three scenarios: low, mid, and high revenue potentials (**Figure 38**) a net profit was only achieved and maintained in the highest revenue potential category, starting from year 2 following offset of capital costs to begin operations. A net loss in profit resulted in both the mid and low revenue potential scenarios, ending in £-123792.7601 and £-218684.50, respectively.

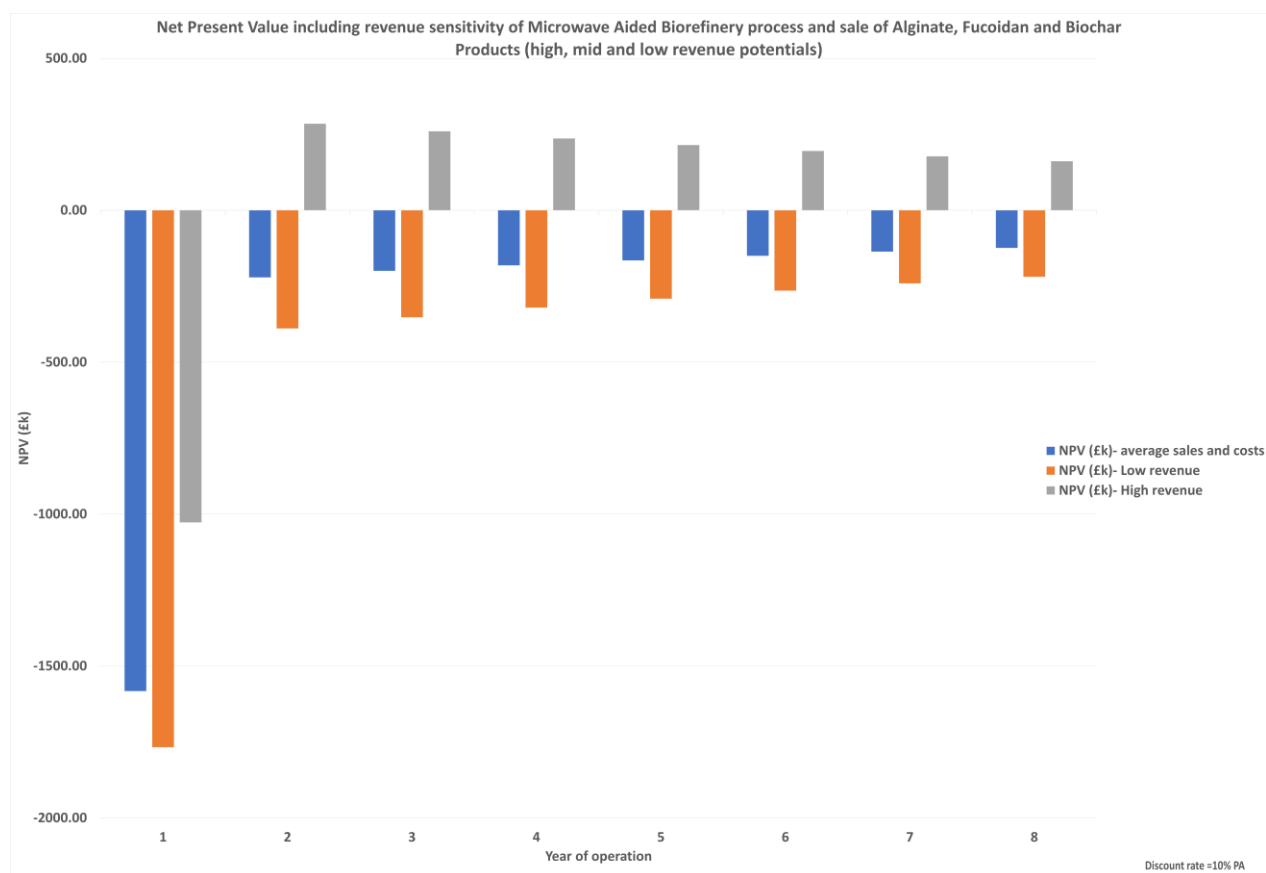


Figure 35- NPV for 3 scenarios in the microwave biorefinerys: mid, low and high value sale prices for alginate, fucoidan and biochar product over an 8 year operation with 10% discount rate.

6.4.Discussion

The techno-economic assessment resulted in the proposal of a novel industrial seaweed process system for advancing understanding in MUS operations. The industrial seaweed process system has the capacity to offer scalable technologies and efficiency (time and energy) based on the combined use of readily available microwave technologies for pre-treatment and added value extraction from seaweed biomass addition to renewable energy infrastructure using Wind Turbines; Solar Panels and a hybrid Hydrogen-Battery energy regulation. The direct coupling of renewable energy infrastructure with the seaweed biorefinery as proposed by this investigation is a novel way for emerging bioeconomic activity to access a secure and stable energy supply for processing and aiming to meet the objective of Net Zero by 2050 imposed on all activity (business or otherwise) in the UK- based on the co-development with clean power technologies from the onset (**Figure 29**). The CMSP offers another distinct techno-economic advantage with the capacity to supply multiple commodities from the operation that reach into higher value markets including pharmaceutical, nutraceutical, cosmetic, food, and lower value including feed and energy (**Figure 29**). The assessment also revealed the financial performance at a high level. Depending on the grade of final products and marketing strategies, it is possible to reach net profit for a microwave-based seaweed process system (**Figure 29**). However, the discounted cash flow analysis also demonstrates the significant variability in the situation owing to the range in the system's performance at production to processing stages and final sale prices for commodities (**Figures 30-35**).

Exploring the potential dynamics (biological and technical) of seaweed aquaculture and a coupled microwave facility using process simulation reveals the possible outputs of each stage. The use and results of the process simulation introduces further details to the proposed CMSP and how a pilot operation may perform with quantitative outputs for system components i.e. seaweed farming, drying and biorefinery. Furthermore, using an expected farming scale (0.25km²) and calculating yield of feedstock in addition to chemical composition, illustrates the potential specifications including microwave power capacity and energy demand, of constructing a downstream facility to process the biomass and generate revenue potential. Although, initial steps have been made to parameterising the CSMP, several uncertainties remain about the operation and high degrees of variability will be present owing to the changes in seaweed growth rates that alter final yield (Van Der Molen et al., 2018), and the chemical composition of the feedstock with differing quantities of sugars, proteins, macro and

micronutrients and moisture content (Schiener et al., 2015) that must be accounted for in the design and operation.

The techno-economic assessment was a further step towards implementation, revealing (at a high level) net profit can be reached in optimal and sub-optimal performance (**Figures 32 & 35**) and effectively raising the technology readiness level of the CSMP (Buchner et al., 2018). However, the results of the sensitivity analysis highlight the high degree of variability within the process system and debt may also be a likely outcome which cannot be recovered by the 2030 deadline set (**Figures 32 & 35**). The wide range in revenue is influenced by the different markets seaweed commodities are distributed to (Balina et al., 2017). For example, dried seaweed biomass can be marketed in nutraceutical and cosmetic categories and thus have a higher value potential than if distributed simply as a bulk food product (Balina et al., 2017; Padam & Chye, 2020). Furthermore, seaweed enterprises used for data extraction in this assessment use different business strategies either as a business-to-business supplier or, in other cases, are a business-to-consumer and thus will have the maximum added value and distributing direct to end consumers (Menzies et al., 2021; The Cornish Seaweed Company, 2023). In the case of the biorefinery, the sugar compounds have a significantly high retail price based on pharmaceutical grade commodities, however, will come with stringent requirements and necessary quality assurance, which otherwise would drop the market retail price significantly- as demonstrated by sodium alginate retailing at pharmaceutical down to food grade applications (Balina et al., 2017; Silva et al., 2017; Wijesinghe & Jeon, 2012).

The biorefinery process performance itself will also vary based on potential fluctuation in the chemical composition of the feedstock, namely, moisture content increasing or decreasing and therefore, needing more or less energy/ time to reach a dried state in addition to changing concentrations of the biochemical compounds that is evident in case studies (Schiener et al., 2015; Sharma et al., 2018). Nevertheless, with tentative confirmation of net profit potential being achievable, the techno-economic assessment and process simulation supports the use of microwave-aided seaweed processing for a flexible and efficient production model. As a resulting of this study can be used to justify further research and development activity in this area to relieve uncertainty and most importantly, advance the prospect of pilot scale operations.

Seaweed biorefinery development for the offshore MUS

Since 2016 the limited understanding of economics in addition to broader development uncertainty surrounding MUS has inhibited any expansion of the concept beyond temporary pilot tests (UNITED, 2020; Van den Burg 2016). Van den Burg's study (2016) highlighted the need for seaweed biorefinery innovation to improve opportunities for co-location, however, research to this end has been limited. Investigations into seaweed biorefinery largely focus on what is technical performance with little to no regard of the situational context these innovations would be placed within (Baghel, 2023). In contrast our assessment used system requirements to determine which technologies/ techniques would be most appropriate and thus providing a situational context for design of a bioresource supply. This led to justifying microwave-based processing because of strategic considerations and meeting system requirements (Table 10), factoring in future development in offshore environments. I also considered the market characteristics of end products, as opposed to generalised minimum selling price of dried biomass which is often used (Nazemi et al., 2021). On the other hand, considering the variability of final prices in live market conditions can drastically alter the conclusions about financial performance of seaweed biorefinery and helps to understand optimal business strategies especially where biorefinery is concerned as pharmaceutical market retail is the only viable route (**Figure 35**). Furthermore, the scope of seaweed biorefinery is typically bounded to the biorefinery stage i.e. fraction and extraction of biochemical substitutes of seaweed (Nazemi et al., 2021). For this study I sought to characterise the overlooked but essential parts of the process systems such as seaweed farming including yield variability and drying pre-treatment with microwaves (**Figure 32**). Focusing on seaweed biorefinery alone in implementation is problematic when considering change in composition is apparent at all stages, firstly, in cultivation at different depths, locations, harvest times etc (Sharma et al., 2018). Moreover, depending on whether seaweed is dried in microwaves, ovens or open air, or frozen or ensiled will all vary the final outcome with changes in composition before biorefinery application has commenced (Badmus et al., 2019). Instead, our assessment sought to prevent this effect with a standardised pre-treatment technology where composition is similar to outcomes of oven drying (Badmus et al., 2019) with distinct technical advantages explained in section 6.3.1.

This study took a new perspective to the offshore MUS. Considering what it would take to realistically develop operations of combined aquaculture and wind farms. In doing so I demonstrated the value in switching attention to nearshore and industrial process system development which in turn has reduced the variability and uncertainty previously shown in Chapter 4's cognitive maps about strategic development in MUS. One key limitation to this study unlike counterparts is the lack of experimental proof-of-concept in the applicable environment. Our modelling had to assume values from existing studies which though proven, may not be the same in every instance and thus gave a wide range of outcomes because of the performance uncertainty (**Figures 32 & 35**). Having the experimental validation would help to determine final product specifications such as purity, emulsifying index and so on, which determines the market applications for seaweed biopolymers (Sodium Alginate and Fucoidan) (Padam & Chye, 2020; Balina 2017). Although, out of scope, it's also not possible to claim for certain the net carbon emission potential of the seaweed process system where existing studies had attempted to clarify the global warming potential (Nilsson et al., 2022).

Towards implementation and the co-development opportunity

Co-developing or co-location of seaweed aquaculture and wind farms is a complex project to manage with little practical experience to-date and uncertainty of outcomes including the risk of debt, that prevents organisations executing the Multi-use Setting design at scale (O'Shea et al., 2022; **Chapter 4**). As discussed in **Chapter 4.4**, the use of pilot projects was recommended in the short term to support development activities offshore. The use of pilots creates "learn-by-doing effect" whereby smaller operations are used to characterise performance, develop understanding and competitiveness of the desired system in preparation for scaling-up/commercialisation of operations (Hellsmark et al., 2016). In the case of the offshore MUS, starting with nearshore production and establishing a suitable processing system for value extraction/ income generation with future intentions to scale-up production offshore, is proposed as such an approach **Chapter 4.4**. Conceptualising the clean-power microwave process system and understanding key economic outcomes provided a critical first step to realisation of a pilot demonstrating a feasible process system that has the capacity to scale whilst attempting to fulfil additional system requirements based on the hypothetical Hornsea MUS case study.

Furthermore, additional benefits that may result were discovered in the design procedure and assessment with the synchronisation potential of the two process systems i.e. seaweed

biomanufacturing and renewable energy. Renewable energy technologies are readily available and were considered out of scope for the techno-economic assessment with known economies of scale and financially viable businesses already active. However, renewable energy infrastructure contains inefficiencies with a growing curtailment of energy potential, equating to 6% of total offshore wind in the UK costing £250,000,000 in 2020 (Staffell et al., 2020). On this basis, I hypothesise at times of low energy demand by the market, energy yield of RE technologies could be directed to the microwave-aided seaweed processing facility. Consequently, optimising performance of clean power infrastructure through use of otherwise wasted energy potential. This arrangement closely aligns with general chemical manufacturing innovators calling for greater integration of renewable power processes in carbon capture storage and utilisation processes such as algal biomanufacturing (Gabrielli et al., 2020; González-Garay et al., 2021). I therefore consider the direct coupling of seaweed processing and clean power technologies a potential route to optimise energy use and economic potential renewable energy infrastructure with a new energy use case and connection to higher value markets via the seaweed supply chain (**Figure 29**).

The conceptual process system designed and evaluated within this study provided a critical first step to the co-development of renewable energy and seaweed biomanufacturing systems with longer term implications for the offshore MUS. The process system provides a means to initiate a pilot process and the learn-by-doing effect to strategically develop offshore innovation considering the uncertainty revealed previously (**Chapter 4.4**). The study reveals a novel innovation that has significant implications not only to the offshore MUS but unexpectedly, addresses resource inefficiencies in the transition to a renewable energy system by optimising the wasted energy potential plaguing clean power technologies. Added benefits of the work include economic viability is plausible and recommended further work towards implementation whilst addressing uncertainties discussed further, below.

Limitations

Prior to development of a real-life system, limitations of this investigation must be addressed. The design procedure for the investigation used empirical evidence drawn from scientific literature in addition to incorporating unstructured consultation that leads to several weaknesses. Firstly, techniques and technologies selected during the C-K design process will carry a bias. This results from the availability/ willingness of collaborators who carry specific domain of expertise and thus may favour their chosen approach/ technology and confirm a hypothesis (Liedtka, 2015). This issue would also be present owing to established businesses (e.g. microwave manufacturing companies) and therefore, will have more information over less mature technologies such as ensilage, that are currently in development and expected to scale in the future (Dussan et al., 2023). Furthermore, information was collected on an informal basis with certain facts unverifiable for the protection of sensitive commercial data otherwise not obtainable and given by few sources that may amplify bias. The challenge for the study was facilitating collaboration and necessitated an unstructured approach to reduce the time demand and fluidity in the design procedure. Further research should focus on challenging the seaweed process design proposed in this study. In contrast to my assessment, I'd recommend a systematic and open design procedure e.g. systematic selection and convening of all relevant parties and use of structured elicitation to capture information in real time with the aim to confirm, reject or modify the conceptual process presented in this study.

Limitations also surrounded the technoeconomic assessment, firstly, some parameter values were unknown and therefore excluded from final calculations including volume and costs of calcium chloride and ethanol to extract sodium alginate and fucoidan polysaccharides (Saji et al., 2022); the annual cost of building and microwave maintenance and the additional costs associated with packaging the final products (dried biomass, sugars, and biochar/feed). Furthermore, where inputs were drawn from known evidence sources, these will contain underlying assumptions and may not reflect every case study including the UK. For example, the cost calculation for the microwave-aided process used assumptions drawn from an Australian study that used the default values within process modelling software (Nguyen & Zhang, 2020). Further research will need to also confirm costs assumptions made, especially, if progressing with a pilot case study that will need to collect real time quotes based on local businesses supplying the needed materials and services for construction.

The techno-economic assessment also presented the range of profitability owing to the changing costs, performance of the process and varying price potentials of commodities that could result in any given year. It is likely the revenue per year will fluctuate with the overall market in addition to the operational performance i.e., quality and quantity of products obtained. The selling prices taken from a retailer's website will only reflect a price point at that point in time and can be subject to change with market conditions. Therefore, stochastic modelling should be used to evaluate process variability and risks and support the further design procedure further (Cardin, 2014). Moreover, with uncertainty in operational performance, industrial scale testing will be needed to evaluate and confirm performance of the process system and find routes to optimisation against technical and economic metrics such as energy demand, costs and time. Factors of importance will include confirming product quality and available quantities and identifying additional parameters critical to evaluating the operation and techno-economic estimations.

6.5. Conclusion

The application of design theory and exploratory techno-economics generated a novel seaweed biorefinery system, revealing an economic opportunity and creating a baseline strategy for co-developing renewable energy and seaweed supply chains. The design procedure identified a process system using defined technologies, that meets several system requirements including scalability, efficiency, and aspects of environmental sustainability (low carbon and reduced waste outputs). The techno-economic assessment illustrated the financial viability (at a high level) of components of said system- given certain conditions being met- and can progress implementation of real-life pilots. Wide ranging revenue potentials were shown, either leading to significantly rewarding outcomes with net profitability or detrimental outcomes with a negative income occurring over the 8 years' time period of operation. Although, the results were a promising start towards implementation of co-developing renewable energy and seaweed supply chain, various limitations must be addressed before realistic progression including validation of the process design presented in this study, confirming operational performance and underlying assumptions in the model, and adding further information critical to accurately estimating the net present value range of the system. Addressing the limitations with further experimental tests, modelling and planning can lead to implementation of a novel process system promoting strategic development of the offshore Multi-use Setting that currently lacks and far-reaching implications for the renewable energy transition through optimisation of energy infrastructure via co-development with seaweed processing.

Chapter 7

Thesis Discussion and Conclusion

The aim of this thesis was to investigate the sustainability consequences of developing seaweed aquaculture inside wind farms to provide management recommendations for implementing MUS within the Circular Bioeconomy transition and review the use of integrated assessment approaches to evaluate the sustainability of Circular Bioeconomy innovations, more broadly. To these ends, sequential methods were applied, with the first three results chapters performing integrative assessments of seaweed aquaculture co-location with wind farms to investigate impacts and risks of development. The final results section uses the information produced by the integrative assessments (IA)/ decision science techniques and applies bioprocess engineering to elicit further information that promotes understanding on the techno-economic consequences of co-developing seaweed and renewable energy systems and provides management recommendations in implementation of the MUS. At each stage, the results were considered in the broader contexts of the thesis, namely, understanding the sustainability implications of the MUS as part of the Circular Bioeconomy transition and how the methods that were used in this thesis contribute to integrative assessment, decision-making and technical activity needed for other bio-based innovations to satisfy the sustainable management criteria imposed on developments. This section summarises and then discusses findings transitioning to a MUS within the Blue Economy context and the value of the IAM approach taken for this project in the broader Circular Bioeconomy transition. Lastly, future research recommendations and concluding remarks about the thesis are given.

7.1. Thesis Summary

The first results chapter has been published previously (O'Shea et al., 2022) and **Chapter 4.1** is under peer review (paper accepted following revisions). Findings of **Chapter 6.1** have been used to form a spinout, private enterprise (Algaecon Ltd, companies house number: 14208977) supported by Innovate UK EDGE Growth programme and Biorenewables Development Centre.

This PhD thesis started by investigating the potential consequences to social, economic, and environmental systems of developing seaweed aquaculture inside a North Sea wind farm to produce information and build conceptual frameworks that can support decision-making under uncertainty in the MUS. The complexity surrounding outcomes of developing seaweed aquaculture inside a wind farm was revealed when attempting to synthesise evidence on the topic, demonstrating a range of changes expected, and the limited information and resources to fully capture the potential dynamics of seaweed aquaculture-wind farm projects and effects to the surrounding ecology (social and natural) (O'Shea et al., 2022). The first research chapter provided the introduction of integrative assessment and conceptual modelling procedure to the MUS, demonstrating the complexity and thus need for an interdisciplinary and collaborative approach alongside appropriate methodologies to reduce uncertainty of impacts in the MUS considering its conceptual state and data limitations of the innovation.

Building on the findings of **Chapter 3**, a diversity of impacts to multi-objective criteria were identified using further evidence collation and an expert panel, from integrating seaweed aquaculture and a North Sea wind farm. The perceived impacts were found to effect multiple levels ranging from changes at the molecular such as genetic reorganisation in natural seaweed populations, to the macro such as climate change mitigation and increased food security, based on the development of seaweed aquaculture activity offshore and expected effects cascading throughout different social-ecological system components (**Chapter 4**). The identified consequences had both positive and potentially costly implications to social, economic, and environmental dimensions that were used for the assessment. The first two results chapters provided the first comprehensive integrative assessment and (qualitative) modelling accounting for social, economic, and environmental objectives and expertise to understand anticipated impacts of developing seaweed aquaculture inside of a wind farm. Moreover, the findings provided a foundation to reduce uncertainty in decision-making in the MUS through identification of plausible impacts and associated information deficits. In addition, a common analytical framework i.e., conceptual maps/ influence diagrams and impact tables were presented, that could be used to facilitate further integrative assessment and modelling techniques including probabilistic analysis, simulations, and risk/ sustainability assessments, to aid management under uncertainty in the implementation of MUS.

In developing seaweed aquaculture inside a wind farm array, trade-offs and risks to environmental sustainability are possible and therefore, would invalidate any sustainability claims of the MUS project as previously made, unless mitigated. The environmental

sustainability trade-offs/ risks based on the SDG objectives includes increasing the presence of invasive species into native habitats; greater mortality or damage to marine wildlife; preventing seabed restoration; induction of ecosystem tipping points and exacerbating climate change (global warming potential) with increased carbon emissions into the atmosphere. Having categorised the potential trade-offs and risks based on collectively agreed objectives, namely, the Sustainable Development Goals, risk evaluation and mitigation activity (data collection, Bayesian Network analysis and/or ecological modelling) can commence to determine the environmental limitations of projects and aim to maximise the benefits by reducing likelihood and severity of deleterious events to the environmental components of sustainability.

Based on the development uncertainties of the MUS and complexity of projects, utilising innovation theory and alternative decision choices and strategic engineering was a promising option proposed to co-developing seaweed process and renewable energy systems including offshore wind farms. Conceptual process designs were made available in **Chapter 6.3** to initiate the synchronisation of renewable energy and seaweed biosystems. One proposed system discovered towards the realisation of co-developing wind farms and seaweed supply chains was combining Wind energy production, an energy regulation unit based on hydrogen/battery infrastructure and a microwave-aided seaweed biorefinery facility supply of dried or cooked biomass; sodium alginate, fucoidan and Biochar/animal feed (**Chapter 6.3**). High level techno-economic assessment reveals the financial potential of the biorefinery system with net profit in some scenarios exceeding NPV of £1 million, but also debt to result-depending on performance of the system from a biological, technical, and economic standpoints. Optimisation and further evaluations (experimental and computational) of the process system will be critical prior to organisations progressing with pilot studies to boost performance and success of operations.

7.2. Thesis Contributions

Multi-objective assessment of the MUS and the Blue Economy

Research into the MUS combining wind farms and aquaculture rarely considered the outcomes and how to approach the development of systems from a multi-objective perspective (Abhinav et al., 2020). The cumulative findings of the research illuminate the potential consequences of the offshore MUS project. Satisfying the multi-objective criteria needed to increase the chances of implementation of the system by gaining community support with improved understanding of outcomes, particularly, reducing likelihood/ severity of negative events and identifying positive contributions (van den Burg et al., 2020a; van den Burg et al., 2020b). Furthermore, integrated management recommendations have been made to the development of the MUS in the context of the Circular Bioeconomy transition. Firstly, the IAM procedure applied to a MUS type system reveals the need for an appropriate strategy to make development economically feasible- arguably the main starting point for realising the multitude of socio-economic benefits. At the current conceptual stage, significant economic risks are present (**Chapter 4.4**) and must be resolved before any real prospect of developing the MUS is made. Moreover, various uncertainties to the wider social and environmental contexts still loom and will need data collection and further analytical methods applied (**Chapter 4.4**). The techno-economic design and assessment presented provides the starting point to lessen the dangers of project complexity and uncertainty by establishing smaller operations with opportunities to optimise and then scale-up in the offshore environment using a suite of engineering and management theories and tools (**Chapter 6.4**) However, in preparation for operations moving into the offshore environment, the conceptual diagrams and risk assessment have given management the needed information to pre-empt problems that could arise for the project and thus increasing coordination towards sustainable development- balancing socio-economic activity with environmental limitations- having already identified variables of key interest (O'Shea et al., 2022; **Chapter 4**; **Chapter 5**). This thesis therefore provides fulfils a major gap in the need for a multidisciplinary analysis of a MUS (Abhinav et al., 2020) providing an immediate assessment of impacts across domains (**Chapters 3-6**). Moreover, the outputs provide the critical entry point to ensure the multi-objective approach to system(s) development is continued within the MUS innovation and has provided a strategy to begin co-developing offshore wind and seaweed sectors.

MUS and the Blue Economy

Chief among the infrastructure to procure and supply cleaner and renewable forms of energy into economy, is offshore wind turbines and farms based on fixed pylon, floating, horizontal and/or vertical axis formats (Barooni et al., 2022; Hevia-Koch & Klinge Jacobsen, 2019; Sun et al., 2021). Resistance to renewable energy developments on land by communities experiencing or perceiving negative impacts to health, local economy, and aesthetic concerns, has also been identified to cause greater favouritism to offshore developments (Devine-Wright, 2005; Susskind et al., 2022b). It is therefore highly likely that significant expansion of offshore wind energy platforms is expected. However, renewable energy installations in the oceans still come with trade-offs to environmental, social, and economic conditions and impose limitations that can extend the timeline and the rate of renewable energy deployment and potentially dampening the progress towards Net Zero by 2050 (Hernandez et al., 2021; International Renewable Energy Agency., 2019; Lloret et al., 2022). On other hand, co-locating with seaweed aquaculture contains the prospect to offset, at least in part, negative social-ecological outcomes of the decision to pursue wind farm projects-only. Evidence and expert perceptions identify enhancements to biodiversity and ecological complexity, absorbing carbon, nutrients and pollutants from the water column, creating jobs and educational opportunities and supporting other local marine industries/ promoting opportunities (**Chapter 4.3**) that could all contribute a net gain of sustainability and promote the Environmental, Social and Governance scores that surround marine developments and gaining stronger community support as a result. Nonetheless, these must balance with the possibility of negatives, or otherwise simply compound existing trade-offs and risks to each projects with added loss of biodiversity, disruption to other marine economic stakeholders and raising tensions in the local communities (**Chapter 4.3; Chapter 5.3.1**).

The Blue Economy has the aim for ecosystem preservation and restoration whilst utilising marine resources to meet socio-economic needs (Bax et al., 2021; Cisneros-Montemayor et al., 2021; European Commission, 2021). This thesis has shown by using IAM that the industrial processes associated with the MUS could, under certain arrangements, meet or exceed, both goals with simultaneous improvements to the socio-economic conditions in monetary and non-monetary terms, and environmental systems including preserving and even restoring ecological networks/functions in a region(s) **Chapter 4**. However, condensing the operations of organisations into a single location brings existing negative implications to social-ecological conditions and new challenges from integrating seaweed and wind energy production that may

otherwise not occur if sited in separate spaces **Chapter 4** and **5**. The issues specific to combining seaweed aquaculture and wind farms are adding complexity and costs to the adjacent organisations (Wind farm maintenance and management), blocking accessibility for other activities such as fisheries inside the wind farm array and shipping and carbon capture storage, and in environmental terms adding carbon emissions to the atmosphere, biosecurity risks and increasing collision potential with avian organisms (O'Shea et al., 2022; **Chapter 4**; **Chapter 5**) It is advisable to continually use integrative assessments and reviews as performed in this thesis for each new, and evolution of, innovations in the marine space. In contrast to this work, examinations should also extend beyond the immediate boundary of an innovation and evaluate the cumulative nature changes to social-ecological dynamics in a region (Jones, 2016; Ma et al., 2023).

The offshore MUS in the UK does not have specific policies or pilot programmes encouraging or examining its development potential. This thesis demonstrates the need for public-private schemes in the UK and beyond for countries looking to implement these types of systems, given the complexity of co-locating marine industries as recommended for general clean technologies by the IPCC working group III (2023). To improve such schemes, it is recommended to incorporate multi-level (e.g. government, research organisations, local community representations and businesses) and multi-disciplinary participation from the social, technical and engineering and natural spaces, and placed under a common analytical framework similar to the output(s) of this research.

IAM of innovations in the Circular Bioeconomy transition

The use of IAM approach has been recommended to better understand the broad social and ecological implications of transitioning to a Circular Bioeconomy. In Wohlfahrt et al (2019) and Bracco et al (2018), sets of indicators have been proposed to collect data and monitor changes in social, economic and environmental conditions at regional to territorial scales. Although, monitoring is beneficial to evaluate ongoing changes, they do not necessarily anticipate trade-offs/ risks until a bioeconomy innovation is established and the pressure(s) are exerted onto the surrounding landscape. On the other hand, applying Decision Analysis and related techniques to a bio-based innovation as performed in this thesis can help to offset said limitations of monitoring-only approaches. The use of group conceptual mapping combined with trade-off assessment had enabled identification of potential detrimental effects prior to implementation of an activity (**Chapters 3-5**). In doing so, follow-up methods can be utilised

to mitigate anticipated risks such as the economy uncertainties as demonstrated in **Chapter 6** providing information for decision-making and a novel strategy proposal for co-developing seaweed and offshore wind sectors.

Using the Decision Analysis process and techniques as an IAM approach in the Circular Bioeconomy also offers a potential route to improve innovation proposals as demonstrated by this thesis and the wider implications of findings. Reductionist approaches to environmental project management can dramatically influence the final outcomes and in certain circumstances amplify trade-offs between the components of sustainability (Howe et al., 2020). The integrative approach utilising Decision Analysis and its related techniques combined with bioprocess engineering presents a new way to evaluate emerging bio-based innovations in the Circular Bioeconomy and can dramatically revise or change conclusions and management priorities based on the systemic oversight. Conceptual mapping and impact assessments revealed the sheer complexity of the MUS situation (the first of its kind) and the highly dynamic and interactive nature of the project whilst still having high degrees of uncertainty that indicates it's impractical to pursue developments at this stage (**Chapter 4.4**). On the other hand, starting with the collaborative integrative assessment, justified the need for bioprocess engineering techniques, however, more importantly, to incorporate system requirements from the offshore MUS context that were otherwise not considered within the design process (**Chapter 6.2**). This then led to a new approach and process system design with far reaching implications outside the original aim of developing seaweed aquaculture inside of wind farms. For example, achieving Net Zero by 2050 means rapid expansion of clean and renewable energy technologies is needed (International Energy Agency, 2022; Chen et al., 2022; DeAngelo et al., 2021). Creative Destruction is an innovation theory that describes the changes to production processes within economic cycles whereby the deliberate dismantling of established processes occurs to make way for improved methods of production (Kivimaa & Kern, 2016; Soete & Ter Weel, 1999). Although, the growth of renewable energy production in the 21st century has continually exceeded expectations, providing cheaper and low-to-zero carbon sources of energy, global emissions and concomitantly global temperatures have continued to rise, putting our chances of achieving Net Zero by 2050 increasingly under threat (International Energy Agency, 2022; International Energy Agency, 2023). Co-developing seaweed and renewable energy systems presents a novel route to optimise the process systems via industrial symbiosis with synergistic benefits between the operations, particularly, direct coupling of renewable energy technologies to high value markets currently inaccessible to the infrastructure (**Figure 29**). Therefore,

diversifying or adding additional revenue streams per unit of Renewable Energy asset I hypothesise this could incentivise investment based on higher financial returns potential of hybrid renewable energy operations and accelerate development potential and climate change mitigation with expanded Net Zero energy infrastructure. Had it not been for the initial application of group conceptual mapping, trade-off assessment and follow-up process engineering, these opportunities would not have been discovered.

In the transition to a Circular Bioeconomy, a significant challenge revolves around the contested sustainability implications of its development, scrutinized through both environmental (biological and physical) and social lenses. Giampietro's (2019) analysis of the Circular Bioeconomy concept using systems ecology and thermodynamic principles highlighted the unsustainable path of shifting to a Circular Bioeconomy. Predicting higher rates of extraction of biological material and coupled ecosystem degradation or a slowdown in economic growth if the (bio-)material flow rate is constrained in some form. However, this thesis highlights the conditional nature of bio-based innovation with specific case studies severely influence the sustainability conclusions e.g. marine vs terrestrial situations. This thesis showed bio-based innovations and the evolving Circular Bioeconomy are not happening in isolation. Instead, there is- occurring or potential for- sector coupling between other technological, infrastructural and policy developments aiming to shift social-ecological systems into sustainable paths such as combining seaweed production and processing systems with renewable energy technologies- as proposed by this thesis. Working at the case study level with an IAM approach rooted in Decision Analysis can reduce the complexity of factors and better characterise innovations for evaluating sustainability implications within the Circular Bioeconomy transition. However, social-ecological systems are complex being open, non-linear and in states of flux and thus individual case study findings will need to be compiled with macro-level assessments (local, regional, territorial and global levels) to address cumulative and emergent properties of collective changes for more robust and accurate predictions of sustainability (Hagstrom & Levin, 2017; Preiser et al., 2018).

7.2.1. Further research opportunities

The results chapters 3-6 of this thesis have identified additional research opportunities pertaining to the multi-objective assessment of the MUS innovation and the integration of clean energy and algal operations through process engineering. A notable gap in the literature is the absence of a structured and routine approach to IAM in the Circular Bioeconomy. Consequently, there is a need to explore the development of a standardized protocol for managers operating in this context. This thesis adopted a comprehensive approach to IAM, focusing on assessing and modelling interactions between various domains. Drawing inspiration from decision science literature in Operations Research (Franco & Montibeller, 2010; French, 2021) and Conservation Science (Hemming et al., 2022), the techniques employed in this study provided invaluable insights into the sustainability consequences of a largely uncharacterized innovation in the Bioeconomy. Despite the richness of available methods and procedures from diverse disciplines due to the transdisciplinary nature of sustainability, there exists an opportunity to streamline and standardise the IAM approach and relevant techniques for effective management during the Circular Bioeconomy transition. A crucial initial step involves compiling all suitable IAM techniques within a Bioeconomy context. Furthermore, these methodologies should be systematically evaluated for their applicability across different stages of innovation, such as the conceptual, experimental, or large-scale commercial operation phases. An assessment of the comparative advantages/disadvantages of one appraisal method over another, such as a comparison between Decision Analysis and Environmental Impact Assessments commonly used in planning applications (Morrison-Saunders & Pope, 2013), is essential.

To facilitate easy accessibility and utilisation of these IAM techniques, a comprehensive catalogue and compilation should be created, forming a practical "handbook" for managers in the Circular Bioeconomy. This handbook would serve as a valuable resource for decision-makers seeking guidance on the most relevant and effective approaches to navigate the complexities of sustainability assessment and management in the context of innovative bioeconomic practices.

7.3. Conclusions

This PhD thesis has significantly advanced our understanding of the sustainability implications associated with co-locating seaweed aquaculture and wind farms. The study not only presents management recommendations for the implementation of this innovative offshore MUS but also critically examines the application of an integrated assessment approach in the broader context of evaluating the sustainability of Circular Bioeconomy proposals.

In essence, the anticipated outcomes of co-location are expected to be substantial and varied, encompassing both positive and negative consequences. These effects extend to ecosystems, impacting both living and non-living elements, as well as influencing social conditions in economic and non-economic terms. Effective project management in such scenarios necessitates continuous systemic oversight, utilising a range of qualitative and quantitative techniques made available through this thesis. These tools are essential for navigating uncertainty and optimising positive outcomes while mitigating negative impacts.

Given the inherent uncertainty and risks associated with co-locations, the recommendation is to initiate pilot programs as an initial step to assess and test the viability of these integrated systems. On a broader scale, the IAM approach, implemented through the Decision Analysis process and related methodologies in this research, proves instrumental in the sustainable evaluation and management of conceptual-level bio-based innovations within the Circular Bioeconomy. Proving to even spinout entirely new strategies to the development of bioresource technologies. This could potentially serve as a foundational step of standardising procedures for emerging innovations. While the IAM approach employed in this study has demonstrated its efficacy, further research is needed to comprehensively explore and catalogue all available methods and approaches to IAM in the Circular Bioeconomy transition. This exploration aims to establish best practices for technology appraisal and environmental management, of emerging innovations and overall evolution of the Circular Bioeconomy.

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Appendix

Table 21- Search terms used in systematic literature review covering the social, environmental, and economic domains.

Search Terms

((“ Marine algae culture” OR “Marine algae farm” OR “Marine algae farming” OR “Marine algae cultivation” OR "Macroalgae Aquaculture" OR "Macroalgae Cultivation" OR "Cultivating Macroalgae" OR "Cultivate Macroalgae" OR "Macroalgae Mariculture" OR "Macroalgae Farming" OR "Farming Macroalgae" OR "Macroalgae Farm" OR "Macroalgae Industry" OR "Macroalgae Production" OR "Macroalgal Aquaculture" OR "Macroalgal Cultivation" OR "Cultivating Macroalgal" OR "Cultivate Macroalgal" OR "Macroalgal Mariculture" OR "Macroalgal Farming" OR "Farming Macroalgal" OR "Macroalgal Farm" OR "Macroalgal Industry" OR "Macroalgal Production" OR "Seaweed Aquaculture" OR "Seaweed Cultivation" OR "Cultivate seaweed" OR "Cultivating Seaweed" OR "Seaweed Mariculture" OR "Seaweed Farming" OR "Farming Seaweed" OR "Seaweed Farm" OR "Seaweed Industry" OR "Seaweed Production" OR "Green Algae Aquaculture" OR "Green Algae Cultivation" OR "Cultivating Green Algae" OR "Cultivate Green Algae" OR "Green Algae Mariculture" OR "Green Algae Farming" OR "Farming Green Algae" OR "Green Algae Farm" OR "Green Algae Industry" OR "Green Algae Production" OR "Brown Algae Aquaculture" OR "Brown Algae Cultivation" OR "Cultivating Brown Algae" OR "Cultivate Brown Algae" OR "Brown Algae Mariculture" OR "Brown Algae Farming" OR "Farming Brown Algae" OR "Brown Algae Farm" OR "Brown Algae Industry" OR "Brown Algae Production" OR "Red Algae Aquaculture" OR "Red Algae Cultivation" OR "Cultivating Red Algae" OR "Cultivate Red Algae" OR "Red Algae Mariculture" OR "Red Algae Farming" OR "Farming Red Algae" OR "Red Algae Farm" OR "Red Algae Industry" OR "Red Algae Production"))

AND

("Impact" OR "Impacts" OR "Risk" OR "Risks" OR "Effect" OR "Effects" OR "Change" OR "Changes" OR "Benefit*" OR "Cost" OR "Loss" OR "Gain" OR "Contribution" OR "Reduction" OR "Alteration" OR "Uncertainty" OR "Uncertainties" OR "Sustainability" OR "Sustainable" OR "Sustainable Development Goals" OR "Sustainable development" OR

"Integrity" OR "Resilience" OR "Stability" OR "Ecosystem Services" OR "Natural Capital"
OR "Social Capital" OR "Financial Capital" OR "Enhancement" OR "Degradation")

AND

("United Kingdom" OR "UK" OR "U.K" OR "U.K." OR "Great Britain" OR "Britain"
OR "British Isles" OR "England" OR "Scotland" OR "Northern Ireland" OR "Wales"
OR "Europe" OR "European Union" OR "E.U." OR "EU"))

Table 22- Search string used in second search as part of the Systematic Literature Review with adjustments made to the location specifications.

Search Terms

(("Marine algae culture" OR "Marine algae farm" OR "Marine algae farming" OR "Marine algae cultivation" OR "Macroalgae Aquaculture" OR "Macroalgae Cultivation" OR "Cultivating Macroalgae" OR "Cultivate Macroalgae" OR "Macroalgae Mariculture" OR "Macroalgae Farming" OR "Farming Macroalgae" OR "Macroalgae Farm" OR "Macroalgae Industry" OR "Macroalgae Production" OR "Macroalgal Aquaculture" OR "Macroalgal Cultivation" OR "Cultivating Macroalgal" OR "Cultivate Macroalgal" OR "Macroalgal Mariculture" OR "Macroalgal Farming" OR "Farming Macroalgal" OR "Macroalgal Farm" OR "Macroalgal Industry" OR "Macroalgal Production" OR "Seaweed Aquaculture" OR "Seaweed Cultivation" OR "Cultivate seaweed" OR "Cultivating Seaweed" OR "Seaweed Mariculture" OR "Seaweed Farming" OR "Farming Seaweed" OR "Seaweed Farm" OR "Seaweed Industry" OR "Seaweed Production" OR "Green Algae Aquaculture" OR "Green Algae Cultivation" OR "Cultivating Green Algae" OR "Cultivate Green Algae" OR "Green Algae Mariculture" OR "Green Algae Farming" OR "Farming Green Algae" OR "Green Algae Farm" OR "Green Algae Industry" OR "Green Algae Production" OR "Brown Algae Aquaculture" OR "Brown Algae Cultivation" OR "Cultivating Brown Algae" OR "Cultivate Brown Algae" OR "Brown Algae Mariculture" OR "Brown Algae Farming" OR "Farming Brown Algae" OR "Brown Algae Farm" OR "Brown Algae Industry" OR "Brown Algae Production" OR "Red Algae Aquaculture" OR "Red Algae Cultivation" OR "Cultivating Red Algae" OR "Cultivate Red Algae" OR "Red Algae Mariculture" OR "Red Algae Farming" OR "Farming Red Algae" OR "Red Algae Farm" OR "Red Algae Industry" OR "Red Algae Production"))

AND

("Impact" OR "Impacts" OR "Risk" OR "Risks" OR "Effect" OR "Effects" OR "Change" OR "Changes" OR "Benefit*" OR "Cost" OR "Loss" OR "Gain" OR "Contribution" OR "Reduction" OR "Alteration" OR "Uncertainty" OR "Uncertainties" OR "Sustainability" OR "Sustainable" OR "Sustainable Development Goals" OR "Sustainable development" OR "Integrity" OR "Resilience" OR "Stability" OR "Ecosystem Services" OR "Natural Capital" OR "Social Capital" OR "Financial Capital" OR "Enhancement" OR "Degradation")

AND

("Greenland" OR "Maine" OR "New Brunswick" OR "Nova Scotia" OR "New Foundland" OR “United Kingdom” OR “Ireland” OR “Belgium” Or “the Netherlands” Or “France” OR “Germany” OR “Denmark” OR “Norway” OR “Sweden” OR “Iceland”))

Table 23- Perceived impacts of integrating seaweed aquaculture and Wind Farms categorised into positive, negative or undefined contributions to the objectives of environmental-focused SDGs based on a trade-off rule review process.

Impact	Pathway to impact	1. SDG objective/ target	2. Positive (support) or Trade-off (counteract) objective	3. Justification of Relationship
Reduction in Climate Active Gases and Global Warming potential	Increased Carbon Sequestration at site on account of farmed seaweed biomass absorbing carbon dioxide during growth and reducing carbon dioxide levels in atmosphere leading to reduce total levels of climate active gases and correlated reduction in	SDG objective 13 "Take urgent action to combat climate change and its impacts"	Positive	Positive relationship proposed based on the conceptual link between the case study reducing global warming potential- a common measure used for evaluating climate change contributions of a project/ process- thus supporting efforts to combat/ reduce climate change

	climate warming potential Loss of cultivated seaweed biomass material from farm and export of seaweed detritus material to the deep-sea creating storage of organic carbon via sedimentation			
Increase to Climate Active Gases	Increased carbon emissions based on new seaweed industry development- see impact "new seaweed industry development"- and added energy demand with coupled	SDG objective 13 "Take urgent action to combat climate change and its impacts"	Trade-off	Negative relationship based on the conceptual link between the case study adding to climate active gases and increasing climate change concluding a counter affect to

	consumption/combustion of fossil-fuels to facilitate seaweed industry activity			combat climate change objective
	Disruption to Wind Farm Vessel operations and increased use time of vessels- see impact "Disruption to Wind Farm logistics/ operations including increased labour and marine vessel use time"- leading to increased fuel demand and coupled carbon emissions			
Reduction in level of Chemicals at and/or around Site and coupled reduction in	Absorption of free-floating chemicals by the farmed Seaweed Biomass during the growth cycle including nitrate/nitrogen, phosphate/	SDG objective 14, target 14.1 "reduce marine pollution of all kinds"... "including	Positive	Positive relationship proposed based on linked concepts/ terminologies between case study reducing nutrient pollution and supporting SDG

Eutrophication potential	ammonia, Carbon, Marine pollutants (unspecified) and heavy metals (Check)	marine debris and Nutrient Pollution"		objective to reduce nutrient pollution
Reduction in Eutrophication potential	Reduction in excess nutrients causing eutrophication potential owing to the increased nutrient capture and removal at site by cultivated biomass	SDG objective 14, target 14.1 "reduce marine pollution of all kinds"... "including marine debris and Nutrient Pollution"	Positive	Related to above*
Increased primary production and nutrient capture efficiency of the ecosystem	Increased primary production of the ecosystem on the account of increased cultivated macroalgae biomass presence at site and coupled nutrient capture from water column during the seaweed growth cycle leading	SDG objective 14, target 14.2 "By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening	Positive	Positive relationship proposed based on conceptual link between case study increasing ocean primary productivity and supporting SDG objective to increase ocean productivity

	to higher overall nutrient capture in ecosystem	their resilience, and take action for their restoration in order to achieve healthy and productive oceans."		
Ocean Alkalisiation	Farmed seaweed biomass absorbing carbon dioxide during growth and reducing carbon dioxide levels in marine waters leading to an increase in the pH levels of waters	SDG objective 14, target 14.3: "minimising/ mitigating the levels of ocean acidification"	Positive	Positive relationship proposed based on linked concepts/ terminologies; Impact causes reduction in ocean acidification and would positively support objective to reduce minimise ocean acidification

Attraction of aquatic biodiversity to site and enhanced habitat structural complexity	Evolution and establishment of ecological community at site on account of increased lower- to-higher trophic biodiversity presence and interactions	SDG objective 14, target 14.2 "By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans." Excluding Timeline issue*	Positive:	Positive relationship proposed based on conceptual link between case study enhancing biodiversity and ecological networks at site and supporting objective of oceanic restoration and ecological preservation
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Limiting Seabed recovery opportunities	Limitations to seabed [nature] recovery owing to the increased sedimentation rates and compositional change on seafloor- see impact “Seabed Sedimentation”	SDG objective 14 and target 14.2: By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans. Excluding Timeline issue*	Trade-off	Negative relationship proposed based on conceptual and linked terminology with case study preventing potential to restore oceanic (seabed) ecosystems
Damage and/or increased mortality of aquatic biodiversity at site	Entanglement of pelagic organisms on account of added structures (seaweed farm infrastructure and	SDG 15, target 15.5 "Take urgent and significant action to reduce the	Trade-off	Negative relationship proposed based on conceptual linkage between case study causing increased mortality of

	cultivated biomass) in water column at site	degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species"		biodiversity and counteracting objective to halt loss of biodiversity
	Decreased benthic community abundance/ compositional change owing to the reduced sunlight access on account of sunlight attenuation at site- See impact "Sunlight Attenuation"			
	Loss of epifaunal species on account of attachment to cultivated seaweed and subsequent removal during harvest of cultivated biomass			

	Disruption to existing organisms on seafloor on account of increased anoxic conditions resulting from the accumulation of biomass on the seafloor derived from the detritus exported and transported from the cultivated seaweed biomass at the site			
Increased stock of Biomass in the Ecosystem	Increased Biodiversity abundance on account of enhanced habitat structural complexity and augmented ecological community establishment at site evolving from seaweed farm (seaweed farm infrastructure and cultivated biomass)- see impact "Attraction of aquatic biodiversity to site and	SDG 15, target 15.5 "Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the	Positive	Positive relationship proposed based on conceptual linkage between case study promoting biodiversity levels in ecosystem and potentially halting loss of species

	enhanced habitat structural complexity"	extinction of threatened species"		
	Prevention of fisheries activity at the site leading to reduce fishing activity and relief from existing fishing pressure at the site allowing the growth of fish stock in the area in addition to the coupled ecological dynamics extending from the seaweed farm (infrastructure and seaweed biomass)- explained in impact: "Attraction of biodiversity to site and			

	enhanced habitat structural complexity”			
Reduced stock of biomass in the ecosystem/ disruption (unspecified) to food web dynamics/ induction of ecosystem tipping point	Reduction and/or disruption in biomass stock/ food web (total) of the ecosystem owing to the decreased higher trophic biomass stock that is limited by the reduced availability of lower trophic food source on account of reduced microalgae primary production- see impact "Reduced Primary Production level of the Ecosystem "	SDG 15, target 15.5 "Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species"	Trade-off	Negative relationship proposed based on conceptual linkage between case study reducing biodiversity levels in ecosystem and amplifying loss of species

Reduced Primary Production level of the Ecosystem	Reduced Phytoplankton (microalgae) primary production on account of nutrient competition induced by the reduced availability of nutrients in ecosystem owing to the increase of nutrient capture by the cultivated seaweed biomass at site	SDG 15, target 15.5 "Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species"	Trade-off	Relationship linked to above*
	Reduced access to sunlight for natural photosynthetic organisms on account of sunlight attenuation- see impact "Sunlight Attenuation"			

Non-native species introduction and biosecurity issues	Augmentation to Marine Virus and/or Bacteria Composition/ Characteristics (undefined) at site owing to the reduced water flow and increased areas for settlement at site on account of added 3D structure (farm artificial infrastructure and cultivated biomass) leading to augmentation effect (undefined), increased presence at site and spread to surrounding habitats with coupled transmission potential of marine viruses/ bacteria into local populations	SDG 15, target 15.8: "By 2020, introduce measures to prevent the introduction and significantly reduce the impact of invasive alien species on land and water ecosystems and control or eradicate the priority species"	Trade-off	Negative relationship proposed based on linked terminologies and concepts of case study introducing non-native species and counteracting potential to reduce impact of invasive alien species
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	Introduction of non-native species to surrounding habitats resulting from promoted dispersal capacity owing the added structure (seaweed farm infrastructure and cultivated biomass) at site			
Genetic Restructuring/ Disruption in Native Seaweed Populations	Establishment of invasive seaweed species and spread of non-native genetic material in natural seaweed populations on account of farming non-native seaweed species at site and subsequent dispersal of spore material from the farmed seaweed species	SDG 15, target 15.8: "By 2020, introduce measures to prevent the introduction and significantly reduce the impact of invasive alien species on land and water ecosystems and control or eradicate the priority species"	Trade-off	Negative relationship proposed based on linked terminologies and concepts of case study introducing non-native species and counteracting potential to reduce impact of invasive alien species

Avian Collision potential with Wind Turbines	Collision rate of bird species with Wind Turbines may increase as a result of the rise in bird presence/activity owing to the biodiversity effects caused by the seaweed aquaculture development- See impacts "Behavioural adaptations including feeding prevention and attraction to site", "Attraction of aquatic biodiversity to site and enhanced habitat structural complexity" and "Increased stock of Biomass in the Ecosystem"		Uncategorised	
Behavioural adaptations including feeding prevention and attraction to site	Reduced foraging/ feeding capacity on account of obstructions to diving zones caused by the added obstacles formed (Seaweed Farm		uncategorised	

	infrastructure) in the water column at the site			
	Behavioural change (characteristics undefined/unknown) resulting from increased presence of structures (seaweed farm infrastructure) available for utilisation by avian organisms			
	Attraction/ increased activity of avian species at the site owing to the increased availability of food (fish) source arising from the increased fish abundance at the site caused by the relief from fishing pressure caused by reduced access rights to			

	site and increased habitat structural complexity at the site.			
Disrupted and/or reduced pelagic organisms' migration	Obstruction to migration paths through the site on account of added structures (seaweed farm infrastructure and cultivated biomass) in the water column at site		Uncategorised	
Disturbance and reduction to Hydrodynamic Flow	Addition of seaweed farm infrastructure and farmed seaweed biomass blocking flow of water through site leading to increase water layer mixing/ reduce water flow/ increased disruption to		Uncategorised	

	hydrodynamics (characteristics unspecified, general)			
Sunlight Attenuation in Water Column	Addition of seaweed farm infrastructure and farmed seaweed biomass blocking sunlight radiation and penetration through the water column at site		Uncategorised	
Seabed Damage/ Scouring	Addition of physical infrastructure (Seaweed Farm Anchors) attached to the seafloor with coupled movement/ flexing of anchorage material		Uncategorised	
Seabed Sedimentation	Loss of cultivated seaweed material (detritus) during growth cycle and exportation		Uncategorised	

	of detritus material to the seabed			
	Addition of seaweed farm infrastructure and seaweed biomass causing block to water flow through the site and diverting sediment material being carried in the water column towards the seabed			

Table 24- Additional assumptions used during techno-economic assessment to compute process outputs including reasoning for assumption, calculation, and data sources.

Assumption	Reasoning	Data Source
Loading rate of 1:10 solute (seaweed) to solvent (deionised water) for microwave reactor where total solute: solvent equates to less than reactor volume.	Existing specifications based on experimental procedures for microwave assisted extraction of seaweed polysaccharides using microwave assisted reaction	(Mcelroy et al., 2023)
A £0.49 per L for supply costs of deionised water	Solvent used for extraction of polysaccharides based on experimental procedures in seaweed microwave biorefinery procedures and price assumption from commercial retailer	(Mcelroy et al., 2023; watnation, n.d.; Yuan & Macquarrie, 2015) -screenshot of retailer price can be found in supplementary materials “TEA model”
Run time of microwave biorefinery process equalling 37 hours multiplied by 52 weeks	Labour input needed for costing process and evaluation performance based on the average full time hours worked by UK workers	UK Office of National Statistics (ONS) average hours of full time worker between January- March 2023 (Office for National Statistics, 2023)

Electricity price of £0.14 per kwh used during microwave applications (drying and chemical extraction)	OpEx cost metric for manufacturing plants. A £0.14 per kWh value selected based on existing electricity cost estimations for commercial enterprises in the UK	(Acha et al., 2022)
35000 kwh for electricity demand covering general business activity and multiplied by £0.14 kwh rate.	OpEx cost metric for commercial enterprise. A £0.14 per kwh value selected based on existing electricity cost estimations for commercial enterprises in the UK and average electricity demand for commercial enterprises in the UK.	(Acha et al., 2022; Business Energy, 2019)
Mass transfer efficiency of alginate and fucoidan in biorefinery process ranging from 1-99%	Evaluating process performance in terms of product outputs based on experimental evidence with differing values and assessing sensitivity of input parameters e.g. industrial scale optimisation vs experimental performance or theoretical maximum and minimums	(Mcelroy et al., 2023; Yuan & Macquarrie, 2015)
Retail price of dried seaweed ranging from £1-79.83 per kg of product	Estimating revenue streams for the microwave drying process based on varied market prices of dried seaweed biomass using values discovered in economic reports of the market and retail price of commercial enterprises	(Menzies et al., 2021; The Cornish Seaweed Company, 2023) -screenshot of retailer price can be found in supplementary materials “TEA model”
Retail price of sodium alginate ranging from £28-299.7+ per kg of product	Estimating revenue streams for the microwave biorefinery process based on varied market prices of sodium	(Merck, 2023a, 2023c; Special Ingredients, 2023)

	alginate using values of retail price of commercial enterprises	-screenshot of retailer price can be found in supplementary materials “TEA model”
Retail price of Fucoidan ranging from £28-299.7+ per kg of product	Estimating revenue streams for the microwave biorefinery process based on varied market prices of fucoidan using values of retail price of commercial enterprises	(Merck, 2023b; TIME Health, 2023) -screenshot of retailer price can be found in supplementary materials “TEA model”
Retail price of Biochar £6.19 per kg converted from €7.11 with 1 Euro:0.87 GBP exchange rate	Estimating revenue streams for the microwave biorefinery process based on UK market prices of biochar found in literature	(Karić et al., 2022)
10% discount rate applied in NPV calculation	Discount rate required as part of NPV calculations and value drawn from existing literature sources of bio-based manufacturing pilot studies.	(Farooq et al., 2020)

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