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Development of a computable general equilibrium model based on integrated macroeconomic framework for ocean multi-use between offshore wind farms and fishing activities in Scotland

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Abstract

The rapid development of offshore wind farms (OWFs) has raised concerns about the increasing conflicts and synergies with existing marine activities, especially the traditional fishery industry, from socioeconomic and environmental perspectives. Quantifying the conflicts and synergies require frameworks that can consider environment and economic systems simultaneously. This study builds on and extends a well-established computable general equilibrium (CGE) model to incorporate a natural capital and ecosystem service into the modelling framework, enabling a comprehensive analysis of the two-way interactions between the economy and natural environment. Our results suggest that expansion of OWFs has significant negative impacts on the seafood sectors, whereas fish stocks benefit slightly as fewer fish are harvested. Moreover, the increase in fish stocks due to the closed areas and artificial reef effect could bring benefits to the fishing sector, and pass onto the wider economy. The combined impacts of expansion of OWFs and increased fish stock demonstrate the potential benefits of multi-use of marine spaces by the OWFs and fishing activities. This modelling approach provides an illustration of the potential and importance of incorporating natural capital into CGE models in practice, which could be used for policy making regarding marine renewable energy and sustainable development planning in the marine environment.

Keywords Natural capital; Ecosystem services; CGE model; Multi-use; Offshore wind energy.

1. Introduction

The economic and societal value of the marine environment is evidenced by the increasing and diversifying human uses of the sea (Austen et al., 2018; de Groot et al., 2012). Activities such as fisheries, aquaculture, tourism, shipping, and offshore energy all benefit from marine resources. In particular, the need for offshore wind energy is increasing due to massive offshore wind resource which is about 329,600 TWh per annum globally (Bosch et al., 2018). Offshore wind has become a cost-competitive renewable energy and the cumulative installation has reached 35.3 GW, accounting for 7% of total global wind capacity by the end of 2020 (GWEC, 2021). Therefore, there is high expectation on annual installation of offshore wind farms (OWFs) reaching 270 GW in 2030 to stay within a 1.5°C global warming (GWEC, 2021). Despite the benefits from good offshore wind resources to provide affordable, reliable, and low-carbon energy, OWFs can also cause conflicts and trade-offs with various existing marine activities (Douvere, 2008), one of which is fishing, a traditional and culturally important marine activity. Moreover, global fish consumption increased significantly by 122%, as a food source, between 1990 and 2018 (FAO, 2020).

As the demand for renewable energy increases, conflicts over resources happen between OWFs and fishing activities. The major conflicts are the use of marine areas. The fishermen are either denied access due to regulatory spatial restrictions or reluctant to fish within OWFs areas (Alexander et al., 2013; Gray et al., 2016; Hooper et al., 2015). The other conflicts are competitions for economic resources, where labour and capital move out of fishing and into OWF development, installation, and maintenance (Blyth-Skyrme, 2010). Meanwhile, OWFs also create synergies with fishing activities. From an ecological perspective, OWF infrastructure could serve as artificial reefs that increase habitat heterogeneity, create food chains, provide shelter and nursery areas, further benefitting local fish populations (Christie et al., 2014; Langhamer et al., 2009; Stenberg et al., 2015; Westerberg et al., 2013; Wilhelmsson et al., 2006; Wilhelmsson and Malm, 2008). In addition, closed areas have also seen reduced fishing pressures because OWFs act as exclusion zones preserving fish stocks (Lindeboom et al., 2011). In the longer term, the improved health of the protected fish stock may lead to a ‘spillover’ of eggs, juvenile and adult fish of commercially important species and bring benefits to fishing activity (Ashley et al., 2014; Coll et al., 2016; Piroddi et al., 2017).

Under the assumption of large-scale deployment of offshore wind in the future, the concept of multi-use (MU), also framed as co-existence or co-location, is designed to help avoid the conflicts and exploit the synergies between OWFs and fishing activities through multifunctional utilisation of marine areas (Onyango et al., 2020). Considering the geographical features of the open ocean space, a spatial analysis confirmed the MU of fishing and OWFs in the North Sea can be a solution for more sustainable and cost-effective options in the energy deployment process (Gusatu et al., 2020). From the social acceptance perspective, the fishermen had more proactive perceptions about the MU while the offshore wind industry showed little interest (Schupp et al., 2021). The stakeholders from different countries showed overall acceptance of MU (Depellegrin et al., 2019 for Mediterranean Sea countries; (Onyango et al., 2020 for North Sea countries) or co-locating OWFs and fishery activities (de Groot et al., 2014; Stelzenmüller et al., 2016; Wever et al., 2015). One economic analysis showed the co-location of aquaculture and OWFs is cost effective and produces both public and private benefits (Kite-Powell, 2017). In general, although there are studies demonstrating the feasibility of the concept of MU to co-locate OWFs and fishing from the ecological, geographical, economic and social aspects, the potential socioeconomic impacts on the overall economy and on the environment are very poorly understood, especially in a quantitative way.

To quantify the socioeconomic impacts of MU between OWFs and fishing, the assessment tool we choose is the computable general equilibrium (CGE) model. A typical CGE model is a theoretically consistent mathematical representation of an entire economy. It has a flexible framework capable of incorporating the environment and thus assessing the impacts of environmental changes on economic performance, the impacts of economic changes on the state of the environment, and the feedbacks between these two (Allan et al., 2018; Banerjee et al., 2016; Comerford, 2017). To help capture the interactions between the economy, society and the environment, we incorporate ecosystem services and natural capital in the CGE model. There are different definitions of natural capital and ecosystem services (Hooper et al., 2019; Jones et al., 2016; NCC, 2014; TEEB, 2013). The definition we choose considers how the stock of natural capital assets (e.g. air, soil, habitats, species) generates ecosystem services (e.g. crops, trees, wildlife) which are used as production inputs to produce goods (e.g. food, timber, recreation) that provide benefits to people (NCC, 2014). The use of the economic notions of “capital”, “stocks”, and “flows” better describes the environment, its functions, outputs, and benefits to humanity (Costanza et al., 1997). The ecosystem services and natural capital can further be valued in monetary terms and thus provides linkages between the environment and the economy (NCC, 2017). The monetary valuation allows impacts of OWFs on ecosystem services and natural capital to be reported in a single metric which can support the use of quantitative assessment tools (Hooper et al., 2017).

Integrating both ecosystem services and natural capital was mentioned by (Banerjee et al., 2016) and was only applied on the land environment (Banerjee et al., 2019 for forest and Banerjee et al., 2020 for land use changes). Natural capital has been integrated into CGE model only for the agriculture (Allan et al., 2018) and forest (Ochuodho and Alavalapati, 2016) sectors but has not been applied on the marine environment. There are previous CGE models that have extended frameworks with links to ecosystem services (Bosello et al., 2011; Carbone et al., 2013) and have been applied on the marine environment such as harvested fish (Finnoff and Tschirhart, 2008; Jin et al., 2012), though not to natural capital such as fish stock. There is a lack of practical application on the marine economy where both natural capital and ecosystem services are linked with the theoretical CGE framework. Therefore, an integrated model is necessary as it would partly resolve the problem of inconsistency between different model outputs and offer a more cohesive narrative to policy makers with a certain degree of flexibility, even if it is only done at an aggregate level (Brouwer et al., 2018).

This paper provides a practical application of developing a novel framework integrating natural capital and ecosystem services into a typical CGE model. Results from such an integrated CGE model are expected to show quantitative changes in economic activities such as how much economic sectors produce, how much households consume, and show impacts on the environment such as whether the natural capital degrades or contributes to economic growth. It is applied to the marine environment for the first time to provide quantitative information for measuring the progress towards sustainable economic development of the ocean (Fenichel et al., 2020). By comparing different scenarios, the results offer a quantitative understanding of the socioeconomic and ecological feasibility of the MU between OWFs and fishing activity.

2. Method

2.1 Model overview

We use our previous Scottish Economy Marine Model (SEMM), which is a comparative static national multi-sector model (Qu et al., 2021). The model is built and solved using the general algebraic modelling system (GAMS). The model is calibrated based on a 2013 Social Accounting Matrix (SAM) for Scotland (Katris et al., 2019).

Producer and consumer behaviours are formulated by functions and solved by first-order optimality conditions under a set of constraints, with producers maximizing their profits while consumers maximizing their utility. Production in this CGE model has a nested structure with multiple levels allowing a degree of flexibility among different sectors, as shown in Figure 1. Production in each sector is determined by constant elasticity of substitution (CES) function that allows substitution between production factors based on relative price changes. Intermediate inputs use is defined using a Leontief function. The production outputs are further combined into a composite commodity under CES functions. There are eight production activities producing seven commodities. Electricity commodity is produced by two production activities, the OWF and the other electricity sectors. The initial assumption is that OWFs account for 10% of total electricity generation. Although this assumption is higher than the OWF share (1%) in total electricity in Scotland in 2013 (SAM data based year) (BEIS, 2019), it provides a useful reference point to identify the present economy-wide impacts of developing OWFs (Arndt et al., 2012).

The commodities can be traded domestically, exported, or imported. The model takes a small-country assumption, which means that any change in Scotland’s export quantity is too small to affect the global price level. Imperfect transformability between domestic sales and exports is expressed by a constant elasticity of transformation (CET) function whereas substitution between imports and domestic goods is governed by an Armington function. On the utility side, there are four domestic demands in the model: household, government, investment, and intermediate inputs for domestic production. The household sector has been further disaggregated into five groups based on weekly income quintiles, with income increasing from HH1 to HH5. The functional form for household utility in this model is a linear expenditure system (LES) which represents a set of linear consumer demand equations to total expenditure. Seafood, particularly aquaculture, is relatively more expensive than other proteins (OECD, 2018; Seafish, 2016). To make a difference between the three seafood commodities, aquaculture is considered as a luxury good for lower income households but a necessity for higher income households. Total government expenditures comprise consumption on commodity formed by Cobb-Douglas utility function. Investment on commodities is assumed as a fixed share of the total investment.

To achieve the equilibrium condition, a set of closure rules are applied. The production factor supply is fixed so that factors are fully mobile between production sectors and the economy-wide wage and capital rent are flexible to clear the market. All government tax rates are fixed; foreign savings are fixed to allow foreign exchange rate to be flexible relative to the external balance under the small-country assumption; and the investment is fixed as the total capital supply is fixed in the model. The GDP deflator is the price numeraire in the model so that price changes are relative changes against the numeraire in the model.

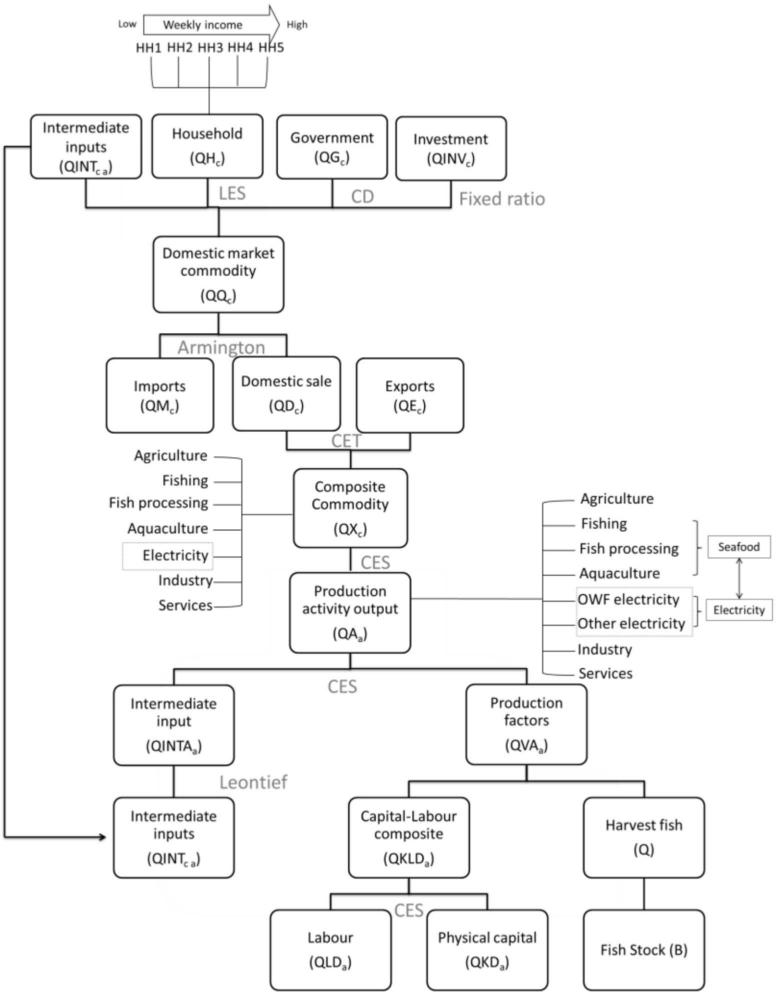

Figure 1 Nested structure of the CGE model

2.2 Environment module

2.2.1 Integration of natural capital into the Social Accounting Matrix

The extension of the CGE model to consider the environment begins with the integration of natural capital into the SAM table. SAM provides the basic accounting structure and benchmark data to a CGE model. The existing economic accounts in the SAM only record economic transactions with market values in the economy. Ecosystem services provided by natural capital are considered as non-monetary market goods and therefore are not included in traditional economic accounts. In order to integrate natural capital into a SAM table, there are three methodological steps to be made through a mix of estimation and calibration, following the guidance for accounting for natural capital and ecosystem services by the System of Environmental-Economic Accounting (SEEA) (UN et al., 2014).

The first step is to distinguish between natural capital and ecosystem services. In most cases, ecosystem services are the direct inputs into economic production or consumption, which bring benefits to the economy. Whereas natural capital is the quantity and quality of natural assets, which provide the flow of ecosystem services. For example, ecosystem services such as fish harvesting depend on natural capital such as the availability of fish stocks but also high-quality habitat (Guerry et al., 2015). In the context of this study, the actual production input is the fish harvested (ecosystem services) provided by the fish stock (natural capital) in the marine environment, resulting in interconnections between the economy and natural environment.

The next step is accounting for and valuing natural capital and ecosystem services using the methodology proposed by (ONS, 2019a). The accounting framework includes assessment of assets and flows. The flow valuation is based on the resource rent which can be interpreted as the annual return stemming directly from the natural capital asset itself (ONS, 2019b). The asset valuation is based on the net present value approach which estimates the stream of services expected to be generated over a certain period of time depending on the type of natural capital (ONS, 2019b). Based on these concepts, Table 1 shows the annual monetary value of ecosystem services (i.e., flow) account in the UK and in Scotland, and the natural capital (i.e., asset) account in the context of fish, from 2007 to 2015. All are adjusted to 2013 prices (which is the same year as the SAM table) using the domestic gross product (GDP) deflator. There was a sharp increase in the provisioning services from fish in 2010, mainly due to a fall in industry cost of fishing production activity (ONS, 2016). Another increase happened in 2014, which was largely driven by a rising catch quota for certain fish species (ONS, 2016). There is annual flow but no annual asset value statistics for fish in Scotland. The published asset value of total Scottish natural capital was estimated to be £273 billion, 37% of the UK total in 2015 (Scottish Government, 2019a). Therefore, the Scottish fish asset value used here is assumed to be 37% of UK fish asset value.

Table 1 Monetary value of annual flow accounts and asset accounts of fish, 2007 – 2015 (£million, in 2013 prices)

	2007	2008	2009	2010	2011	2012	2013	2014	2015
Annual flow in UK	318	275	280	392	309	310	302	334	328

Annual flow in Scotland	80	88	86	109	101	86	90	96	86
Asset value in UK	11,131	11,221	11,435	11,997	11,952	11,963	12,222	12,537	11,986
Asset value in Scotland (37% of UK)	3,785	3,815	3,888	4,079	4,064	4,068	4,155	4,263	4,075

Source: Author's own calculation based on ONS, 2019b, 2019a, 2018, 2016; Scottish Government, 2019a);

The last step is to integrate the natural capital and ecosystem service accounts into the SAM table. There is one stock account representing natural capital and one flow account representing ecosystem services. To be distinguished from physical capital in the traditional SAM table, the owner of natural capital is not assumed to be households nor government. An environmental sector is therefore created in the SAM table as the source of natural capital supplying ecosystem services for production inputs and for receiving corresponding payments (Allan et al., 2018; Banerjee et al., 2016; Comerford, 2017). An environment account is created as the owner of natural capital, and a natural capital account is created to supply ecosystem services, as shown in Figure 2. The production activities use ecosystem service as a production factor input so that there is one cell between activity and natural capital accounts representing the factor input. The environment account therefore receives payments as 'capital income' by sectors using ecosystem services, shown in one cell between the natural capital column and environment row. The use of ecosystem services by production activities provides positive contributions to economic output but also causes depletion of the corresponding natural capital in the environment. Hence, one more cell between the environment column and the activity row is required to represent the cost to the environment for supplying the natural resources. To distinguish natural capital from man-made capital, the latter is referred as physical capital in the SAM and the model. In general, the environmentally extended SAM table highlights transactions between the economy and the environment by creating the natural capital account and the environment account. The value of ecosystem services and natural capital in the SAM should equal the annual flow and asset of fish in Scotland in 2013 as shown in Table 1.

Although the methodology has been suggested by SEEA, there is limited practice of integrating natural capital into the system of national accounts (Brandon et al., 2021). The application of environmentally extended SAM to the ocean economy is particularly insufficient (Fenichel et al., 2020). This study attempted a practical application of such methodological framework integrating marine natural capital and ecosystem values into the Scottish SAM. Furthermore, the applications of linking SEEA accounts with CGE modelling are limited (Jendrzejewski, 2020), which could better capture the feedbacks between both economic and ecological systems.

	Activities	Commodities	Factors	Households	Corporation	Government	Investment-Savings	Rest of World	Total (Income)	Natural capital	Environment
Activities		Domestic supply							Activity income		Cost of environment
Commodities	Intermediate Inputs			Households Consumption		Government Consumption	Investment	Exports	Demand		
Factors	Value-added (Labour, Physical capital)								Factor income		
Household			Factor income		Transfers	Transfers		Transfers	Household income		
Corporation			Factor income			Transfers		Transfers	Corporation income		
Government	Production taxes		Factor income	Income Taxes	Taxes			Transfers	Government income		
Investment-Savings				Household Savings		Government Savings		Foreign Savings	Savings		
Rest of World		Imports			Transfers	Transfers			Foreign exchange inflow		
Total (Expenditure)	Activity expenditures	Supply	Factor expenditure	Household expenditure	Corporation expenditure	Government expenditure	Investment	Foreign exchange inflow			
Natural capital	Ecosystem services as input factor										
Environment										Capital ‘income’	

Figure 2 General representation of the integration of natural capital into the SAM table (Adapted from Banerjee et al., 2016).

2.2.2 Incorporating environment module into the CGE model

After integrating natural capital and ecosystem services into the SAM table, the SEMM framework needs to be adjusted to include the extra environmental sector and build the linkages between the economy and the environment. Figure 3 shows a schematic diagram integrating the environment within a CGE model. The environment module is linked with the standard SEMM model, allowing the economic processes to affect fishing productivity and output and ultimately the level of fish stock. The technical innovation of the SEMM-Environment model is that it endogenously integrates ecosystem service and natural capital within one framework. The fishing sector demands not only physical capital and labour like other sectors, but also specifically harvesting fish as a factor input. In this SEMM-Environment model, the harvested fish used as production factor represents an ecosystem service, which is provided by natural capital, i.e., fish stock.

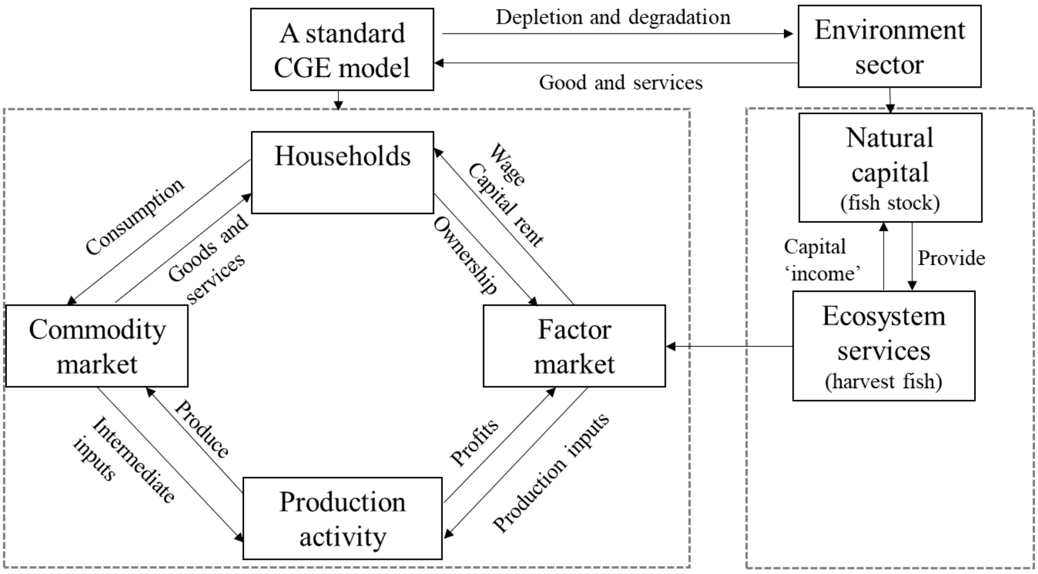

Figure 3 Flow chart of the structure of the CGE model with environment as a new sector (Adapted from Allan et al., 2018)

To integrate natural capital and ecosystem services into the model, first a logistic biological fish stock function is applied (Banerjee et al., 2016):

$$B_1 = B_0 + \left[\gamma B_0 \left(1 - \frac{B_0}{k}\right)\right] - Q \qquad (1)$$

where B_0 is the initial fish stock, B_1 is the fish stock after harvesting, Q is quantity of fish harvested, γ is intrinsic growth rate of the resource stock, and k is carrying capacity of the environment. Equation (1) shows the fish population dynamic of changes in fish stock after harvesting. The calibration of parameters like γ and k can be derived from Table 1 by choosing opening and closing asset values as B_0 and B_1 as well as corresponding annual flow value as Q.

Then the harvested fish is defined by a classical harvest function from bio-economic analysis (Banerjee et al., 2016; D. Di Jin et al., 2012):

$$\mathrm{Q} = \mathrm{q} \times B_0 \times \mathrm{E} \qquad (2)$$

where q is catchability coefficient, and E is fishing effort. Based on Equation (2), for a fixed catchability coefficient and a given fishing effort, the harvest fish is positively correlated to the initial fish stock. This function shows a fish harvesting function, which assumes that catch per-unit of effort is proportional to the existing stock.

The next step is to modify the production function for the fishing sector, which uses harvested fish (Q) as a production factor along with physical capital and labour:

$$Q = \alpha \times F(L_a, K_a) \;\; for\; a = fishing \qquad (3)$$

where L_a is labour and K_a is physical capital. In Equation (3), harvested fish (Q) is shown as function of labour and capital. By linking Equation (2) with Equation (3), the associated stock levels B_0 and catchability coefficient q are incorporated into the shift parameter (α) (increase in B_0 refers to $\alpha > 1$) while the fishing effort E is a function of corresponding physical capital and labour inputs $F(L_a, K_a)$. Therefore, both fish stock (B) and the ecosystem service it provides (Q) are endogenous variables in the model so that the linkage between the economy and natural capital has been established. Previous studies model the effect of changing stock size by modifying the function for the fishing sector at the top production level as additional to intermediate inputs and value-added (Banerjee et al., 2016; Jin et al., 2012). To better allow flexibility, ecosystem service is considered as a factor input and placed at the second level of production structure in the SEMM (Figure 1). In this way, the SEMM-Environment model considers the state of the natural capital and the ecosystem services to ensure a more holistic and comprehensive representation of the natural environment is linked with the economic system.

2.3 Scenario settings

We designed three scenarios to demonstrate the functionality of the SEMM-Environment model to analyse the two-way linkages between the economy and the natural environment (Table 2). As the settings of parameters would bring uncertainty to the model results, a sensitivity analysis is conducted to test the validity and robustness of the model results. The results of sensitivity analysis are presented in the Appendix.

Scenario 1 focuses on the impacts on the environment from the economy by increasing the output of OWFs by 340%. The magnitude of this increase is based on the difference between the current capacity of 0.94 GW in 2021 (Scottish Government, 2022) and a consented capacity of 4.1 GW (Scottish Government, 2019b). This significant increase in output is implemented in the model by adjusting government subsidy on the OWF electricity sector.

Scenario 2 evaluates how changes in the environment affect the economy. As there are no existing quantitative assessments of fish stock changes due to OWFs, the assumption concerning increased fish stock is based on similar effects observed in marine reserves. (Roberts et al., 2001) reported a 3-fold increase in the biomass of five commercially fished species in marine reserves in three years. Using this as a reference, it is assumed that there is a 300% increase in fish stock due to the OWFs since closed areas and artificial reef effects operate like marine reserves in this scenario. Changes in fish stock are implemented by changing the parameter α in Equation (3). The increase in fish stock would be expected to directly benefit the fishing sector, with knock-on effects to the other seafood sectors and the wider economy. As Scenario 2 only considers increases in the fish stock but does not include direct economic impacts of expanding OWFs, it provides a reference for Scenario 3 to compare with.

Scenario 3 examines the combined impact of a 340% increase in output of OWFs and a 300% increase in fish stock. This scenario simulates the economic potential of marine MU by the fishing sector and OWFs together, covering both the conflicts and synergies. By comparing the results across these three scenarios, this SEMM-Environment model provides a two-way understanding of the impacts of OWFs on the economy and the environment, and the feedbacks between them.

Table 2 Simulated scenarios for Scotland in the SEMM-Environment model

Model scenario	Impacts	Assumptions made	Shocks in model
Scenario 1	From economy to environment	Expansion of OWFs	340% increase in output of OWFs sector
Scenario 2	From environment to economy	Increase in fish stock	300% increase in fish stock

Scenario 3	Feedback between economy and environment	Co-location of fishing activity and OWFs	Combine the above two

3. Results

The results focus on the variables from three parts: production, environment and household behaviour. The production includes output (QA_a), labour and physical capital demand (QLD_a, QKD_a) as shown in Figure 4, and sales (QQ_c) and their prices (PQ_c) as shown in **Figure 5**. The environment module (Figure 6) includes fish harvested (Q), fishing effort (E) and fish stock after harvesting (B_1). Household behaviour (Figure 7) consists of household income, consumption (QH_h), and welfare. Welfare compares the cost of pre- and post-shock levels of consumer utility, which is measured as Hicksian equivalent variation in monetary terms (in million pounds). All results are reported as relative changes from the 2013 SAM baseline values apart from welfare, which is considered as a change in monetary value (in £million).

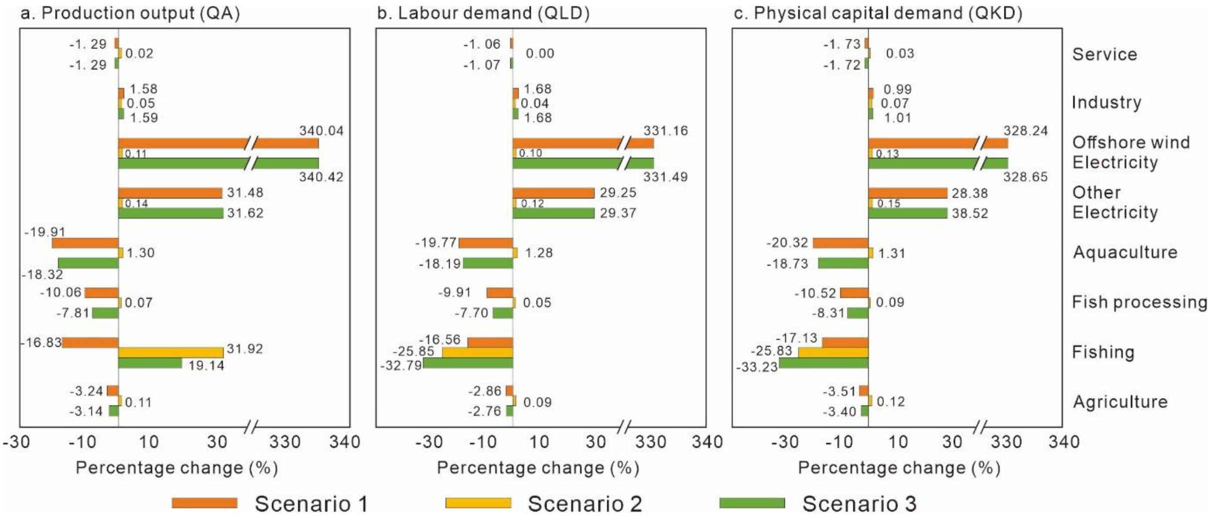

Figure 4 Relative changes (%) from baseline values for variables of (a) production output, (b) labour demand and (c) physical capital demand for different scenarios

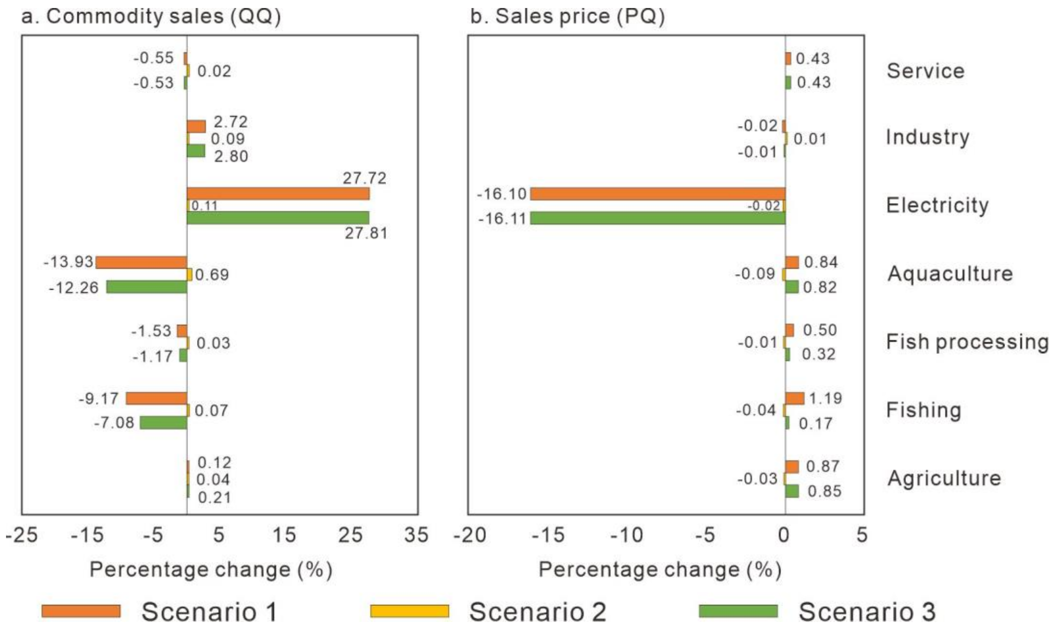

Figure 5 Relative changes (%) from baseline values for variables of (a) commodity sales and (b) sales price for different scenarios

3.1 Scenario 1

Scenario 1 results indicate that the electricity sectors increase their production output due to OWF expansion, with correspondingly increased labour and physical capital demand. As a result of the subsidy, a fall in electricity price leads to increased electricity sales. In contrast, most other sectors decrease their production at different rates. Most heavily affected, in relative terms, are the three seafood production sectors (i.e., fishing, fish processing and aquaculture). The fishing sector’s output exhibits a relatively large decrease, together with a reduction in fishing effort. However, in terms of natural capital, the fish stock actually has a small (0.36%) increase, benefitting from less fish being harvested (-16.98%) by the fishing sector. Outputs in the aggregated agriculture and service sector decrease by a smaller proportion. The industry sector increases output slightly as the expanding electricity sectors need more industrial inputs for production. The changes in commodity sales are consistent with their production outputs, but typically by a lesser extent. In particular, seafood commodity sales decrease with higher sales prices.

All five household groups have slightly decreased income in Scenario 1. In percentage terms, the decrease is largest for the three mid-income household groups (i.e., HH2, HH3 and HH4) due to their relatively greater participation in factor markets. The consumption changes are consistent with the income changes. The variation in household consumption behaviour is that higher income households tend to have larger change in consumption as they have reduced income. Similar variations also exist in household welfare changes. Lowest income households lose least welfare (£23.39 million) while higher income households tend to have more welfare loss (£196.74 million).

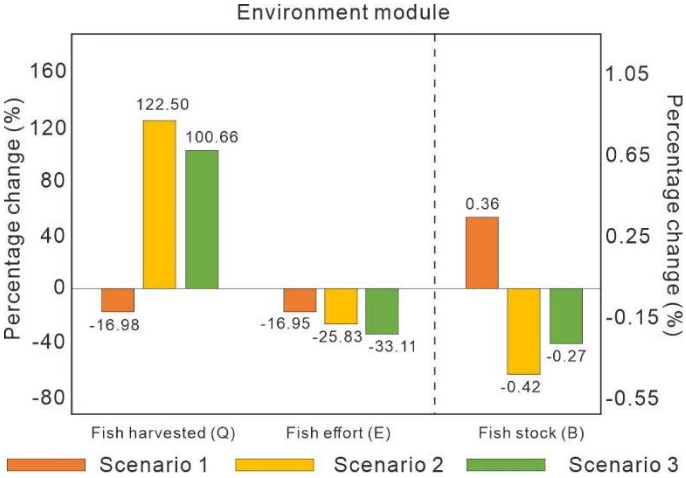

Figure 6 Relative changes (%) from baseline values fish harvested, fish effort (left axis) and fish stock (right axis) of the Environment module for different scenarios

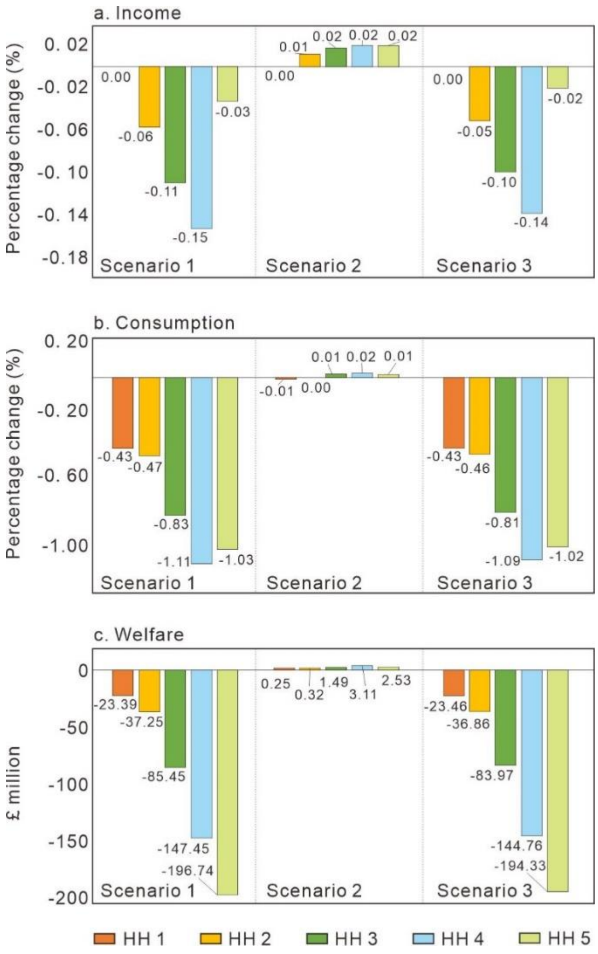

Figure 7 Relative changes from baseline values for variables of (a) household income (% changes), (b) household consumption (% changes), and (c) welfare (£million)

3.2 Scenario 2

Scenario 2 model results indicate that in general, increasing fish stock due to closed area and artificial reef effect has significant impacts on the fishing production but generally small knock-on impacts on the economy. The 300% increase in fish stock leads to a significant 31.92% increase in the fishing production output. There is not only more harvested fish (122.51%) but also decreasing fishing effort indicated by less labour and physical capital needed in production (-25.83% and -25.85% respectively). The aquaculture sector experiences the second largest increase in output. The remaining sectors show small increases in outputs. The overall increase in all production has positive impacts on commodity sales with cheaper prices. The benefit from the increase in fish stock is passed on to households, though the changes in household income and consumption are very small (less than 0.02% generally). As for household welfare change in monetary value, all household groups make a small welfare gain, ranging from £0.25 million to £3.11 million. The higher income households (HH4) have the highest welfare gain.

3.3 Scenario 3

In Scenario 3, the impacts are dominated by the expansion of OWFs so that the results are similar to Scenario 1, except for the fishing sector. With an increase in fish stock, the fishing sector increases its output (19.14%) but to a smaller extent and correspondingly less fish harvested (100.66%) compared to Scenario 2, due to labour and physical capital taken away by expanding OWFs. It should be noted that the combined impacts of the expansion of OWFs and increased fish stock on the economy are not simply additive. The increase in OWF electricity output is slightly (0.3%) higher than the sum of increases in Scenarios 1 and 2. It is more significant in the seafood sectors where increase in fishing output is higher (4.1%) while reductions in fish processing (2.2%) and aquaculture (0.3%) outputs are less than the sums in Scenarios 1 and 2. This is because the natural capital approach feeding back into the CGE model is able to capture non-linear effects that could be presented as behavioural responses to changes in the economy (Waters and Seung, 2010)..

All household groups experience a slightly decreased income, the variations of which have similar patterns as in Scenario 1. The percentage decrease in income is greatest for the three mid-income household groups. Consumption decreases in all households. All households have welfare loss ranging from £23.46 million for the lowest income household group (HH1) to £194.33 million for the highest income household group (HH5). The impacts on welfare are also not simply additive. Compared to the sums of welfare changes in Scenarios 1 and 2, households tend to loss less welfare in general.

4. Discussion

4.1 Economic impacts

The model results first show how the economic activity interacts with environment. The expansion of OWFs would negatively affect most sectors, as demonstrated in Scenario 1. The negative impacts are on average larger in relative terms for seafood sectors than for highly aggregated sectors, because production factors (labour and physical capital) are taken by expanding OWFs. The competition over constraint production factors corresponds with a crowding-out effect: production sectors could divert physical capital from other sectors to expand production through pricing up the relative rentals (Hu, 1972; Mercure et al., 2019). It could be interpreted from an empirical perspective that fishermen and fishing vessels could be used to provide support services or surveying for OWF projects (Blyth-Skyrme, 2010). Less labour and physical capital available for fishing activity result in a reduction in fishing effort and fish harvested and ultimately a slight increase in the fish stock. Scenario 1 therefore illustrates how expanding OWFs protects fish stocks and acting as de facto marine reserves (Ashley et al., 2014; Bailey et al., 2014), from a quantitative macroeconomic perspective.

The model then implements environmental shocks and finds out how the whole economy reacts. Previous work confirms the existence of closed areas and artificial reef effect (Langhamer, 2012; Maar et al., 2009; Reubens et al., 2013), though there is still a lack of quantitative evidence on whether the seafood sectors and even the economy could actually benefit from it. Scenario 2 uses closed area and artificial reef effect as environmental impacts and confirms the economic gains. It is achieved through reduced fishing effort from more available harvested fish and results in redistribution of labour and physical capital, leading to benefits for sectors such as the aquaculture and electricity sectors. Some sectors are also positively affected due to increasing seafood used as production inputs through the supply chain (Seung and Kim, 2020), such as the fish processing and service sectors. Therefore, such positive impacts from the environment side could pass onto the overall economy to a small extent.

After confirming the interconnection between economy and environment, the model explores the economic and environmental impacts of MU intervention. The potential benefit from increasing fish stock could sufficiently offset the negative impacts on seafood production brought by OWF expansion, as shown in Scenario 3. Such co-production of energy and food from sensible planning has been demonstrated to balance land use between food production, energy production and ecosystem service supply, to achieve ecological sustainability, and to maintain food and energy productivity (Bakshi et al., 2015; Hanes et al., 2018). Our results provide macroeconomic evidence that similar co-production in the marine environment could be achieved by the MU which would sufficiently benefit from synergies to mitigate the conflicts between OWFs and fishing activities.

Furthermore, the model presents results on household welfare. The assessment of welfare is particularly useful to policy-makers as they tend to justify their decisions in terms of welfare improvement (Karabulut et al., 2016). The reduced welfare in all households in Scenario 1 reinforces the idea that subsidizing the renewable energy could cause welfare loss for households as they receive less income (Johansson and Kriström, 2019). Lower income households lose less welfare as energy uses take larger proportion in their spending so that they benefit more from cheaper electricity. On the contrary, all households in Scenario 2 could benefit from increased seafood supply and gain welfare, especially higher income households as they tend to consume more seafood (DEFRA, 2017; Kearney, 2010). Such welfare gain from increased fish stock could slightly mitigate the welfare loss from subsidising the OWFs, as shown in Scenario 3. Therefore, the above findings confirm the importance of benefits on economic activities gained from ecosystem service and further contribute to raising the awareness about human dependence on natural resources (Franzese et al., 2017).

By capturing two-way interrelationships among components of ecological and economic systems, our integrated framework can provide valuable insights into the potential trade-offs and synergies of OWFs expansion on the economy and the environment. These outcomes highlight the conflicts and synergies between OWFs and seafood production as well as the importance of application of the CGE modelling framework to improve natural capital and ecosystem services valuation.

4.2 Ecosystem service valuation and natural capital accounting: implications on policy and management

The creation of natural capital and ecosystem services approach aims to raise awareness of the economic significance of the environment and captures the feedback from economic activity to the environment (Bunse et al., 2015). Ecosystem services are essential to economy as they are taken as essential inputs to production or welfare gain to people through recreation and appreciation of nature, which are generally provided by natural capital as an important asset in the environment. Only focusing on the trends in the economy is insufficient as increases in economic benefits from ecosystem services can be achieved by overexploiting natural capital (Guerry et al., 2015). Meanwhile, benefits on the environment from economy side may come at a high cost. In our model, Scenario 1 quantitatively demonstrate how changes in economic activities would have impacts on provisioning ecosystem services and therefore on the sustainability of natural resources. However, such increase in natural capital stock comes at a relatively high cost from a cost-benefit perspective. This means that the economic losses for seafood sectors (i.e., decreased outputs) are much larger than the ecological gains in terms of increasing fish stock, due to the generally slow recovery rate of fish stock (Hutchings and Reynolds, 2004). It is important to consider the long-term sustainability of fish as natural capital and the sustainable economic well-being of fishing communities from an economic perspective (Waters and Seung, 2010). Scenarios 2 and 3 show that the economy could benefit from OWFs through the artificial reef effect, as long as fishermen are able to get access to the increased fish resources. Therefore, ecosystem services and natural capital are useful natural resource management tools, by taking into account the costs and benefits to the natural environment, and by highlighting clearly the implications for economy and human wellbeing (e.g., Picone et al., 2017). As the decision-makers need to have a full understanding of the trade-offs between economic benefits and the long-term sustainability of natural capital (Bizikova et al., 2013; Hanes et al., 2018), the model results provide quantitative foundation to consider the potential synergies between OWFs and fishing and encourage the policy of MU between suitable fishing activities and OWFs.

Monetary valuation of ecosystem services and natural capital would support evaluating the scale and magnitude of impacts and thus raise awareness of the importance of environment to policy makers (Bunse et al., 2015; de Groot et al., 2012). Previous studies show that variations in ecosystem services will have substantial influence on agricultural productivity and enhance the food security (e.g., Bommarco et al., 2013; Fezzi et al., 2014). Our work further extends the impact assessment towards the overall economy and provides information needed for economic analysis and policy-making relevant to MU at national level by further incorporating natural capital into a CGE model. Such an integrated framework is able to explore the economic and environmental impact of a range of policies which could be assessed from economic production, ecosystem services, and natural capital perspectives and be linked to the wider economy (Allan et al., 2018). With this integrated framework, the trade-offs and synergies between OWFs and seafood can be considered as a whole to avoid depletion of natural capital, to achieve sustainability for ecosystem services, and to better consider both seafood and offshore renewable energy production. Therefore, our integrated SEMM model is a useful tool for the consideration of resource efficient policies, allowing evaluation of the potential benefits of alternative options for resource allocation across economic sectors as well as environmental assets.

4.3 Multi-Use between OWFs and fisheries

Marine renewable energy and seafood production are expanding due to increasing demand of low carbon energy and sustainable food source from the marine environment. MU platforms that can combine many functions within the same infrastructure through co-located technologies. It could be a future tendency for OWF development, which could bring significant benefits in terms of lowering energy production cost, optimising marine spatial planning, and avoiding the impacts on the environment (Stuiver et al., 2016).

Our model results fill in the gap of confirming the socioeconomic benefits on production and household welfare provided by provisioning ecosystem services through co-locating the OWFs and fishing, demonstrating the importance of developing MU in the marine environment rather than focusing on offshore renewable energy development solely. Besides the provisioning ecosystem services assessed in our model, studies have shown positive effects for fish and benthic species and communities, including an increase in the biodiversity around turbine foundations from supporting services (Inger et al., 2009). For regulating services, increase in mussel has been observed that is likely to increase the capacity of the system for waste remediation and carbon sequestration (Potts et al., 2014). For cultural services, the OWFs could act as new recreational opportunities for tourists to visit these places (Westerberg et al., 2013), which may bring benefits through the development of MU platforms. Taken all above benefits from ecosystem services into consideration, they could further enhance the theoretical ecological foundation for MU. Furthermore, MU platform could develop promising technical synergies. Offshore wind arrays can offer protection to fish stocks and should therefore co-locate with fishing activities or around the fish farm cages (Zanuttigh et al., 2016). The offshore wind turbine could also be designed to provide the energy to create an artificial upwelling of the nutrient-laden waters from the deep to increase the surface fish production and thus bring more benefit to the fishing activities within the areas (Viúdez et al., 2016). By benefitting from ecological, technical, and socioeconomic evidences, the development of OWFs under MU is a feasible direction to maximize the synergies, optimize efficient use of marine space, and promote the use of resource diversity (Schupp et al., 2019).

Although our model identifies the socioeconomic opportunity to deploy MU, the existing projects addressed in European seas mainly supported by public funds and subsidies, showing the novelty of such MU platforms (Abhinav et al., 2020; Depellegrin et al., 2019). For example, The MERMAID project explored the possibility of using innovative multi-purpose platforms for combining aquaculture with offshore wind and wave production (Christensen et al., 2015; Stuiver et al., 2016). The TROPOS project presented an integrated offshore multi-use approach combining transport, energy (floating offshore wind farm), aquaculture (fish and algae) and leisure (Papandroulakis et al., 2017). The MUSES project highlighted MU potential practices of fisheries in OWFs in the UK (Kafas, 2017) and Germany (Schupp and Buck, 2017). Besides, a plurality of ocean MU cases covering different combinations of offshore wind with other activities have been investigated, such as aquaculture (Holm et al., 2017), oil (Legorburu et al., 2018), fisheries and protected areas (Gusatu et al., 2020), nature conservation and seafood (Steins et al., 2021), wave and aquaculture (Zanuttigh et al., 2016). It can be concluded that the majority of existing MU projects focus more on hybrid wind-wave energy devices, with a few including aquaculture systems and little attention on fisheries. In reaching the EU targets for offshore wind energy deployment, the multi-use of space with fisheries should attract more attention to become a potential sustainable solution for reducing conflict in the marine environment.

4.4 Constraints in the modelling approach

CGE models have been criticised for the large number of parameters (i.e. elasticities) that need to be estimated (Arndt et al., 2002). Integration of natural capital into a CGE model adds more complexity and uncertainty to the modelling work in terms of parameter calibration and data availability, especially natural capital accounting and valuation of ecosystem services. Most studies that have attempted to link economic and ecological systems have overcome many of the challenges by simplifying one or both of the systems (Carvalho et al., 2011). This SEMM-Environment model makes similar simplifying assumptions, including the choice of a linear relationship linking harvested fish and fish stock through a classic fish harvest function and a lack of limitation from maximum sustainable yields. Multiple types of natural capital interact to generate ecosystem services and harvesting fish depends on not only the availability of fish stocks but also other natural capital like high-quality habitat (Guerry et al., 2015). Furthermore, our framework only covers provisioning ecosystem services, and quantitative impact assessment for many ecosystem services is still lacking, mainly due to data limitations (Hooper et al., 2019). These are not included in the model assumptions, which may not fully reflect the complexity within the economic and ecological systems involved.

Future research could consider integrating various ecosystem services and natural capitals into the CGE model to better understand the trade-offs and synergies between OWFs and seafood production. There are already other studies that quantify (in monetary terms) the impacts of OWFs on cultural ecosystem services, primarily recreation (Börger et al., 2015; Ladenburg, 2010; Westerberg et al., 2013) and aesthetic values (Ladenburg and Dubgaard, 2007). Instead of being direct production inputs in the economy like provisioning ecosystem services, cultural ecosystem services are often treated as a final good to be directly consumed by households so that an increase in household income will stimulate the value of the ecosystem services as consumers are more willing to pay for them (Allan et al., 2018; Carbone et al., 2013). How to integrate the other two types of ecosystem service still remains unknown mainly because they affect human wellbeing but their values are not observable from market transactions (Kite-Powell, 2017). Other types of natural capital could also be considered to be integrated in the framework, such as the wind resource itself as a type of natural capital to be used as inputs in the OWF electricity production (ONS, 2016).

5. Conclusion

Although the rapid development of OWFs will help increase energy security and reduce carbon emissions, there are potential trade-offs and synergies between OWFs and fishing activities. Therefore, an explicit assessment of the impact of OWFs on fishing and the ecosystem services upon which fishing activities rely is necessary to inform the sustainable management of marine areas in the context of MU.

Our SEMM-Environment model first aims to build an integrated framework to assess the impacts of deploying OWFs on the sustainable use of natural capital and the provision of ecosystem services, simultaneously considering interplays between economy and environment. The model results suggest that OWFs expansion has negative impacts on fishing and seafood production, but this reduced fish output actually conserves the fish stock to a small extent. It provides quantitative evidence when analysing the de-facto marine protected areas that are created by exclusion zones around OWF infrastructures. Meanwhile, the increase in fish stock due to closed areas and artificial reef effect would bring benefits largely confined to seafood production and minor impacts to the rest of the economy. Such results fill in the quantitative gap of whether fishermen could economically benefit from increased natural capital and prove that ecological benefits could be translated into economic gains. Furthermore, it has been demonstrated how the methodological framework can be used as a tool for evaluating the economy-wide consequences of the MU policy. The combined effects of OWFs expansion and increased fish stock demonstrate that it would be sufficient to mitigate part of the negative impacts of OWFs on fishing production and the knock-on impacts on seafood production. The model results highlight the potential trade-offs and synergies between offshore wind energy and seafood production by endogenizing feedbacks between the economic system and changes in natural capital stocks.

Our model then serves to generate awareness among policy makers of holistic thinking about the role of natural capital and ecosystem services in the economy. SEMM-Environment model makes the attempt to integrate natural capital and ecosystem services with CGE models to show the two-way interrelationships and feedbacks between the economy and the environment: environment provides goods and services to economy while economy causes depletion or degradation to the environment. The model is able to conduct analyses which policy makers can examine how OWFs will impact social and economic factors, also how the environmental impacts will affect these factors. Our key findings demonstrate that to avoid ecosystem service degradation and maintain economic productivity, taking natural capital and ecosystem services approaches into consideration is necessary as ecosystem services sufficiently provide the synergies and mitigate the conflicts from both economic and environmental side.

The results of our SEMM-Environment model will also be useful for the consideration of future development of MU between OWFs and fishing activities in the marine environment. Our results represent an important step in quantifying the conceptual understanding of ocean MU and will assist developing policy concerning both socioeconomic and environmental impacts. Such results could help inform policy makers with useful insights regarding generating co-benefits to reduce conflicts and offset the costs of developing OWFs in the context of MU concepts, which would help achieve renewable energy targets while avoid the adverse side effects on fisheries.

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Appendix

Sensitivity Analysis

The tested parameter is the elasticity between physical capital and labour (ρ_a^{va}) in the fishing sector. The initial value of this elasticity is set at 0.3 representing a complementary situation. The sensitivity analysis increases this elasticity to assume high complementary (ρ_a^{va}=0.8), low (ρ_a^{va}=2), medium (ρ_a^{va}=5) and high substitution (ρ_a^{va}=8).

The results of sensitivity analysis (Table A1) showed the robustness of the results. As the elasticity of substitution between labour and physical capital increases, the fishing output has slightly smaller reduction (from -0.17% to -0.16%) in Scenario 1 and a smaller increase (from 0.19% to 0.20%) in Scenario 3. Such slight changes could be explained by physical capital is the constraint factor for the fishing production. Greater ease of substitution between these two inputs implies that a higher level of labour input can be used to mitigate the impacts from competition over physical capital. Increasing elasticity has almost no impact on the output of the fishing sector in Scenario 2. It can be concluded from the sensitivity analysis that: with increasing elasticity of substitution between labour and physical capital, the direction of impacts of OWF expansion on the fishing sector is consistent, whereas the magnitude of such impacts has slightly variations depending on different scenarios.

Table A1 The sensitivity of the output of the fishing sector to alternative values of the elasticity $\boldsymbol{\rho_a^{va}}$ (% change)

	Complementary (ρ_a^{va}=0.3)	High complementary (ρ_a^{va}=0.8)	Low substitutable (ρ_a^{va}=2)	Medium substitutable (ρ_a^{va}=5)	High substitutable (ρ_a^{va}=8)
Scenario 1	-0.17	-0.17	-0.17	-0.16	-0.16
Scenario 2	0.32	0.32	0.32	0.32	0.32
Scenario 3	0.19	0.19	0.19	0.19	0.20