Impacts of Offshore Wind Energy on Seafood Sectors: A Macroeconomic Perspective of the Energy-Food Nexus

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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

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Abstract

The rapid expansion of offshore wind farms (OWFs) in response to increasingly ambitious renewable energy and climate targets in the UK has led to growing concerns about conflicts and synergies with existing fishing activities. The complex relationship between energy and food in the marine environment needs to be explicitly evaluated from an energy-food nexus perspective. On one hand, developing OWFs has potential to reduce GHG emissions and increase energy security through diversifying energy supply and providing domestically produced electricity. On the other hand, the expansion of OWFs could have fish supply implications through impacts on seafood production.

There are indirect linkages between OWFs and fishing activities through limited economic production factors, influenced heavily by market forces, and direct linkages through physical and environmental interactions, driven mostly by policies and management practices and affected by ecosystem dynamics. These complex linkages could lead to both negative and positive impacts of OWFs on seafood production and consequently availability and affordability of food supply from the marine environment. Through indirect economic linkages OWFs can affect the demand, supply and prices of the production factors such as labour and capital needed by the seafood production sectors. In terms of direct physical and environmental linkages, the exclusion of fishing activities from OWF areas could result in a decrease in fish landings while reduced fishing activities and artificial reef effect provided by OWF structures could have positive impacts on preservation of fish stocks.

To quantitatively evaluate this marine energy-food nexus from a macroeconomic perspective, a static computable general equilibrium (CGE) model is developed, using Scotland as a case study. A particular focus is on the disaggregation of (i) the electricity and seafood sectors to explicitly reflect their economic interconnectedness in order to better model the impacts on availability of food and energy security; (ii) the household groups with different income levels to concentrate on the affordability of energy and food and the distributional effects on welfare. To better emphasise the physical and environmental linkages, two additional modules are created in the model. The innovative marine resource allocation module simulates the spatial conflicts between OWFs and fishing activities while integrating the natural capital and ecosystem services approach

further extends the modelling framework to analyse feedbacks between economy and environment. There are therefore three versions of the CGE model, each with a different focus and structure.

The first one uses the basic structure of the CGE model to assess the near-term, indirect impact of decreasing cost of OWFs through economic linkages. The results suggest that high cost under subsidy and low cost of OWFs would have positive impacts on energy security and limited negative impacts on seafood production sectors. In particular, the falling cost of electricity from OWFs would have a small positive impact on the economy overall and benefit lower income households, contributing to the reduction in fuel poverty.

The second application includes marine resource as an additional production factor and creates a novel marine resource allocation module within the model to better capture the physical interactions between expanding OWFs and fishing activities. The model shows that massive expansion of OWFs results in increasing energy security but significant negative impacts on seafood supply as marine resource is taken away from fisheries by expanding OWFs.

The third application integrates natural capital, represented by fish stock, into the CGE model to evaluate the environmental impacts of OWFs considering ecosystem dynamics and feedbacks. Expanding OWFs would reduce fishing output and thus preserve fish stock. However, the artificial reef effect of OWFs would increase the fish stock, eventually benefiting fishing output. The combination of these two opposing impacts suggests that the artificial reef effect is sufficient to mitigate the negative impacts of expansion of OWFs as long as fishermen could get access to the fish stocks close to OWFs.

Overall, the model results demonstrate that expanding OWFs would enhance energy security but also bring negative impacts on fish supply. Therefore, there is a need for integrated management of food and energy in the marine environment. To minimise conflicts and maximise synergies from the nexus perspective, co-locating OWFs and fishing activities through marine spatial planning could be a possible solution. The modelling framework is also applicable to other marine renewable energies to assess their potential impacts on energy security and seafood supply, and on the wider economy.

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List of Abbreviations

CD	Cobb-Douglas
CES	Constant elasticity of substitution
CET	Constant elasticity of transformation
CfD	Contract for difference
CGE	Computable general equilibrium
CPI	Consumer price index
EV	Equivalent variation
FEW	Food-energy-water
GAMS	General Algebraic Modelling System
GDP	Gross domestic product
GHG	Greenhouse gas
LES	Linear expenditure system
IO	Input-Output
MSP	Marine spatial planning
NCA	Natural capital accounting
OWF	Offshore wind farm
SAM	Social accounting matrix
SEEA	System of Environmental-Economic Accounting
SEMM	Scottish Economy Marine Model
SDG	Sustainable development goal
ROW	Rest of World
RUK	Rest of UK

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1. Introduction

1.1. Background: from the food-energy-water nexus towards the energy-food nexus in marine environment

Food, energy and water are fundamental resources for human wellbeing, but are facing increasing pressures. The external pressures are mainly from rapid world development in the form of population growth and mobility, economic development, international trade, urbanisation, diversifying diets, cultural and technological changes, and particularly climate change (Hoff, 2011). It is predicted that this growing pressure will increase global demand by 2050 in the order of: 60% for food (FAO, 2014a), 55% for water and 80% for energy (OECD, 2012). An additional effect of this growing demand is increasing competition for resources between food, energy and water since they are intrinsically interconnected and dependent on each other through production and consumption linkages. For example, water is needed for cooling of power plants and for irrigation in food and biofuel production, while energy is used for food and water production, and food crops and agricultural land more widely can be used to produce biofuels. Changes in any of the three systems will have impacts on the other two. For example, increasing food production would lead to increased energy and water use (Bazilian et al., 2011). As a result, the three resources should be considered together within an integrated framework that is able to capture the interconnections. This will help to avoid or minimise conflicts as well as create or maximise synergies in the collective management of all three sectors.

The concept of the food-energy-water (FEW) nexus was developed to capture the interrelations, synergies and trade-offs between the uses of resources and to promote security of the three nexus elements across the different domains of the environment, economy and society (Hoff, 2011; World Economic Forum, 2011). There are three main reasons to employ a nexus approach in studies (Albrecht et al., 2018). First, nexus framework could improve resource use efficiency or security by eliminating the trade-offs and reinforcing the synergies to find the balance among the development of the nexus resources (e.g. De Laurentiis et al., 2016). Second, nexus thinking helps enhance policy integration when dealing with interactions between nexus elements (e.g. Smajgl et al., 2016). Third, the nexus framework has been promoted as a conceptual tool for achieving those sustainable development goals (SDGs) that concern sustainable management for economic development, social equity and environmental protection (e.g. Ringler et al., 2016).

To support sustainable use of natural resources and better environmental decision making, further refinements of the nexus concept recognize the need to incorporate ecosystem services and natural capital in a system-wide nexus framework (Bizikova et al., 2013). There are several definitions of natural capital (Hooper et al., 2019; Jones et al., 2016; NCC, 2014; TEEB, 2013). Natural capital in this thesis is defined as the stock of natural assets (e.g. air, soil, habitats, species), which provides a wide range of goods and services (e.g. crops, trees, wildlife) called ecosystem services (NCC, 2014; UK NEA, 2011). The ecosystem services in turn are used as production inputs to produce commodities (e.g. food, timber, recreation) providing benefits to people. Therefore, the ecosystem services approach focuses on the interactions between environment and human well-being (Fisher et al., 2009; MA, 2005). There are four types of ecosystem services provided by natural capital, including provisioning, cultural, regulatory and supporting services (Häyhä and Franzese, 2014; Hooper et al., 2019). In this context, food, energy and water are provisioning ecosystem services that can be directly used as inputs to economic production (de Groot et al., 2010). The natural capital and ecosystem services approach therefore raises awareness of the economic significance of the environment and captures the feedback from economic activity to the environment (Bunse et al., 2015), making it a useful natural resource management tool (e.g. Picone et al., 2017, Hooper et al., 2019; NCC, 2017). The benefits of bringing together ecosystem services and natural capital with the nexus approach lie in the simultaneous consideration of socioeconomic goals and environmental sustainability. Therefore, FEW nexus is proposed as a framework specifically to identify synergies and trade-offs across food, energy and water within the economic domain, inform sustainable use of natural resources within the environment domain and facilitate formulation of more integrated policies within the social domain (Nielsen et al., 2015).

Strong policy drivers exist to reduce greenhouse gas (GHG) emissions, reduce dependence on volatile-price conventional fossil fuels, and diversify energy supply. These have led to rapid increases in renewable energy technologies. Renewable energy sources are considered to be a key element in the FEW nexus in terms of increasing energy security and energy system transformation towards sustainability (Böhringer and Löschel, 2006). However, as the FEW nexus implies, increasing energy security could have diverse and multiple consequences on other nexus elements. Furthermore, it is likely to have a higher impact where resources are already under pressure (FAO, 2014b). Considering renewable energy development within FEW nexus approach is therefore essential in order to highlight the interactions with other key natural resources and so improve resource management decisions and thus progress across different SDGs (Figure 1.1).

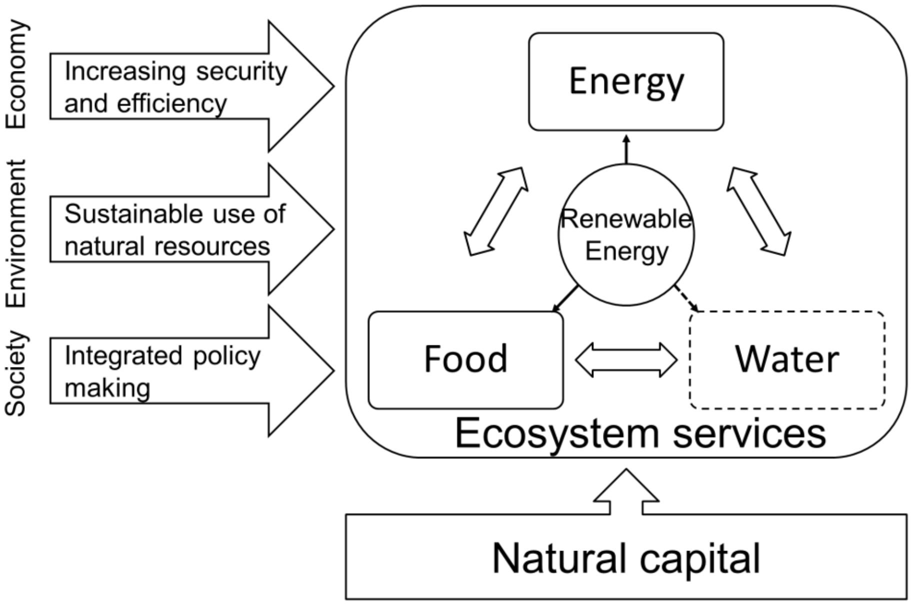

Figure 1.1 Integrated ecosystem services and natural capital with FEW nexus framework (Adapted from Bizikova et al., 2013)

1.1.1. The energy-food nexus in the marine environment

Wind energy generation has been the second largest growth sector in renewable energy, both offshore and onshore (IEA, 2019). Wind energy does not rely on large sources of freshwater as other conventional sources of energy do (Snyder and Kaiser, 2009), which could ease the burden on limited energy and water resources in the FEW nexus. Compared to onshore wind, offshore wind farms (OWFs) have advantages including being located where steadier and higher winds can produce more electricity and having lower visual impact (Green and Vasilakos, 2011; Rodrigues et al., 2015), which has led to the rapid growth of the sector. Global installation of offshore wind increased by 41% in 2019 compared to the 2018 market, reaching 29 GW in total (GWEC, 2019). The UK led these deployments, with a total of 9.6 GW installed capacity, contributing to 45% of all

OWF capacity in Europe (The Crown Estate, 2019). To meet the reducing GHG emission target and increasing energy security, the plans for further development of OWFs are definite for some countries, for example China, Japan, Brazil, and Australia (GWEC, 2019).

Despite the benefits from good wind resources to provide affordable, reliable, and low-carbon energy, OWFs can also cause potential conflicts with other uses of the marine environment, particularly fisheries. Seafood, mainly fish, has been a traditionally important source of nutrition around the world (Béné et al., 2015; Beveridge et al., 2013). Globally, fish is the principal source of animal protein and makes up about 20% of their average per capita intake of animal protein (by weight) for 3.2 billion people (FAO, 2018). Global fish consumption increased on average by 3.2% per year between 1961 and 2016 (from 9.0 kg/capita in 1961 to 20.2 kg/capita in 2015), a rate which exceeded that of meat from all terrestrial animals combined (2.8%) (FAO, 2018). Marine dominates the world fishery production (79.3 million tonnes), which contributed to 87.2% of the world's total (90.9 million tonnes) production in 2016 (FAO, 2018). An increase in seafood consumption and a decrease in wild fish stocks raises the importance of increased support for open ocean aquaculture (FAO, 2018). Capture fisheries (79.3 million tonnes) still accounted for 73% of total marine fisheries and aquaculture (108.0 million tonnes) in 2016 (FAO, 2018). However, as a source of food supply, aquaculture will continue to grow faster than other major food production sectors, at a 2% growth rate per year (OECD-FAO, 2019).

As an important source of protein, globally fish consumption is growing, meanwhile the demand for offshore wind energy is also increasing. The conflict between OWFs and fisheries is therefore likely to intensify. Therefore, there is a need to assess the impacts on both food and energy security that arise from the interactions between offshore wind energy provision and marine fisheries from an energy-food nexus perspective. Previous FEW nexus analysis on renewable energy has been concentrated on the terrestrial scope such as bioenergy and hydropower production (Conway et al., 2015). It has not yet been applied to the marine environment, which also is vulnerable to changes induced by economic and social pressures (Austen et al., 2018). Since fresh water is not directly involved in offshore wind energy generation and marine fisheries, the nexus framework in this thesis will focus on the energy-food interactions only.

To better evaluate the energy-food nexus involving offshore wind energy and seafood production, the first step is to understand the historical trends of both nexus elements. Secondly, identifying and unpacking the nexus interconnections between the two is needed to assess the trade-offs and synergies from both economic and environmental perspectives.

1.1.2. Energy sector overview: offshore wind energy development in UK and Scotland

The UK Government plans to reach net-zero GHG emissions by 2050 under the Paris Agreement (HM Government, 2019). The UK energy mix is thus moving towards electrification with the increased electricity supply generated from renewable energy technologies providing low-carbon, sustainable energy resources (National Grid, 2019). The share of renewable energy in total electricity generation reached 37% in 2019 (BEIS, 2019a). Furthermore, renewable energy would become more competitive if GHG emissions would be priced through a carbon tax mechanism (GWEC, 2019). It is forecast that the electricity generation capacity needed in the UK will rise from around 62 GW in 2016 to between 65 to 85 GW by 2050 (National Grid, 2017). Renewable energy thus plays an important part in the electrification and decarbonisation of the UK energy system.

Among all sources of renewable energy, OWFs experienced the fastest development in the UK. During the last decade (2009 – 2019), the installation of OWFs has continuously increased and its share in total electricity generation reached almost 10% in 2019 (see Table 1.1). The location of all operational OWFs and those in construction is shown in Figure 1.2. Further development of OWFs is expected to meet the additional electricity generation capacity needed, which could reach 8 – 18 GW by 2025 and 16 – 30 GW by 2050 (National Grid, 2017). The UK government has also stated its ambition of 40 GW of OWFs by 2030 (The Crown Estate, 2019).

Table 1.1 Offshore wind electricity capacity and generation in UK (Source: BEIS, 2019a)

Year	Cumulative installed capacity (MW)[1]	Annual electricity generation (GWh)	Share of electricity generation (%)
2009	951	1,754	n.a.
2010	1,341	3,060	0.8
2011	1,838	5,149	1.4
2012	2,995	7,603	2.1
2013	3,696	11,472	3.2
2014	4,501	13,405	4.0
2015	5,094	17,423	5.1
2016	5,086	16,406	4.8
2017	6,951	20,916	6.2
2018	8,169	26,687	8.0
2019	10,141	32,146	9.9

Despite the fast growth of offshore wind, the pace of development in the UK has been mainly affected by technology advancement and the availability of government support schemes such as Contracts for Difference (CfD). CfDs incentivise the development of new energy technologies (which typically have higher costs) by guaranteeing a typically subsidised stable sale price for electricity generation amidst volatile wholesale electricity prices while protecting consumers against higher bills (BEIS, 2018a). With the support from CfDs, the capacity of OWFs has increased by over 400% while costs have fallen by more than 60% after three auction rounds (AR). As shown in Table 1.2, the successful OWF projects won support in the most recent AR3 at a strike price of around £41/MWh. The record-low and subsidy-free price has made offshore wind one of the lowest cost options for renewable energy in the UK, even cheaper than gas. This new price made offshore wind more competitive and would further stimulate its future development as a renewable energy. Additional reductions in the cost of offshore wind energy are still possible to achieve with innovative technology

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[1] Cumulative capacity at the end of the year

and more experience in deployment (BEIS, 2016; IRENA, 2018; Wiser et al., 2016).

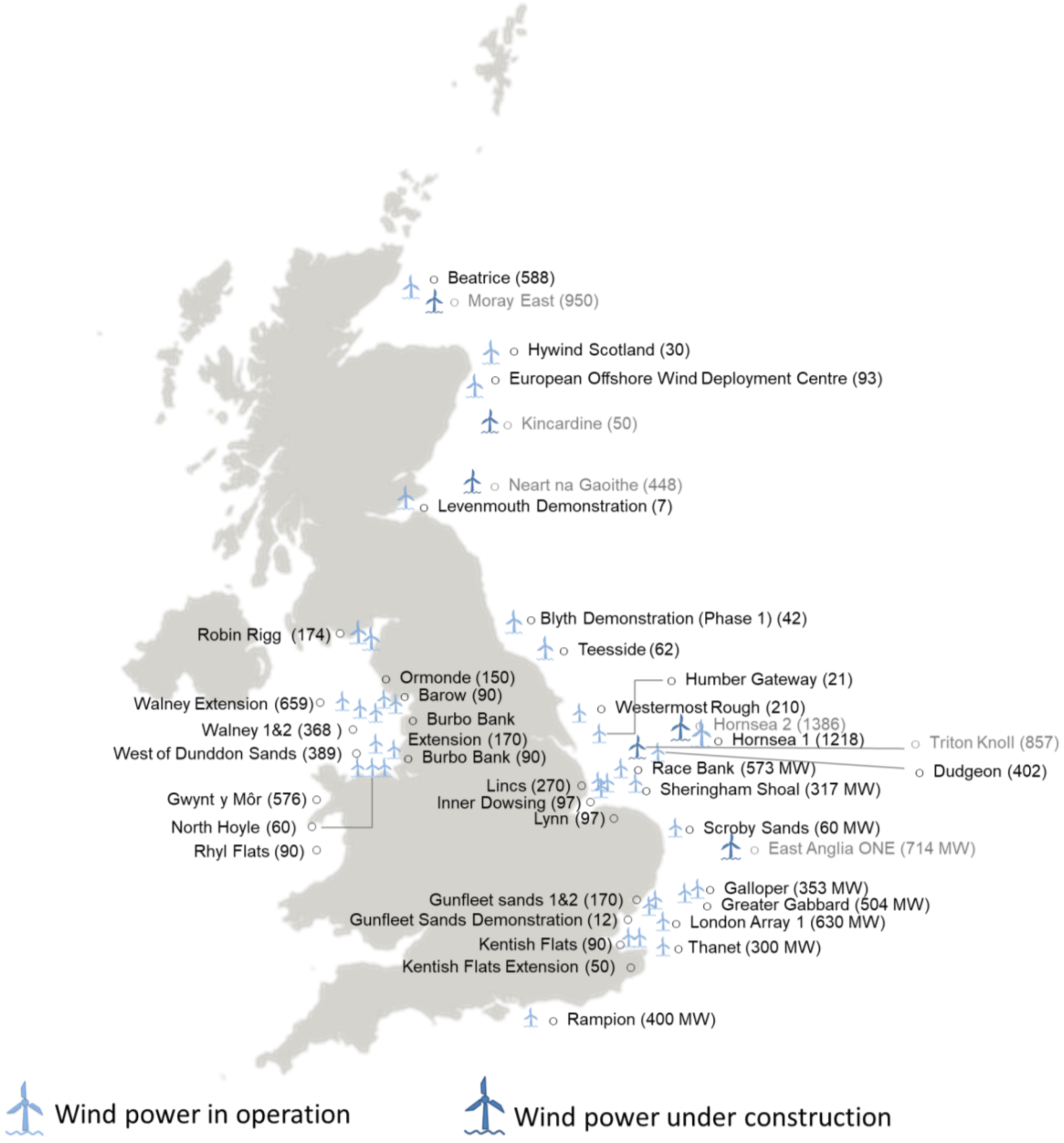

Figure 1.2 UK operational and constructing offshore wind farms as at 31 December 2019 (Source: The Crown Estate, 2019a).

Table 1.2 Three Rounds of Contracts for Difference Allocation of Offshore Wind Energy in UK (all prices are adjusted to 2012 prices) (Source: BEIS, 2019b, 2017, 2015a; Ofgem, 2019).

CfD Allocation round (AR)	Year	Total UK capacity (MW)	Scotland capacity (MW)	Average strike price (per MWh)	Average wholesale electricity price (per MWh)
AR1	2014	1162	448	£117	£48.2
AR2	2017	3196	950	£64	
AR3	2019	5466	466	£41	

At the level of the devolved administrations, the Scottish Government has set an ambitious target to generate 100% of Scotland's gross annual electricity consumption [2] from renewable sources, including offshore wind, by 2020 (Scottish Government, 2018a). The latest figure showed that 76.2% of gross electricity consumption in Scotland came from renewable sources in 2018 (Scottish Government, 2019a). For OWFs, Scotland was slow to extend its installed capacity after the first commercial OWF came into operation in 2010, but has experienced a rapid expansion since 2017 (Table 1.3). By 2019, Scotland had 981 MW of operational OWFs, contributing to almost 7% of total electricity generation (BEIS, 2019a).

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[2] Gross electricity consumption measures total generation minus net exports. It is equivalent to total consumption plus generators' own use plus losses.

Table 1.3 Offshore wind electricity capacity and generation in Scotland and its share in the country's total generation of electricity (Source: BEIS, 2019a, 2019c).

Year	Cumulative installed capacity (MW)	Annual electricity generation (GWh)	Share of electricity generation (%)
2011	190	604	1%
2012	190	540	1%
2013	190	587	1%
2014	197	569	1%
2015	187	539	1%
2016	180	502	1%
2017	210	614	1%
2018	580	1371	3%
2019	981	3183	7%

However, Scotland has significant potential for further offshore wind development with a significant proportion which is an estimated 25% of European's total offshore wind resources due to a combination of high wind speeds and abundant deep water sites (Scottish Government, 2018a). Most operational OWFs use conventional fixed bottom substructure technology whereas floating wind turbines, an emerging new technology, are attached to the seabed by chains and anchors and therefore have more potential for growth with less water depth related constraints (Scottish Government, 2019b). The exploitable wind resource in Scotland is estimated at 46 GW of fixed (162 TWh per year) and 123 GW of floating (537 TWh per year) installations (The Offshore Valuation Group, 2010). Scotland is therefore considering the potential to continue expanding offshore wind energy for up to 10 GW by 2030 (Scottish Government, 2019b). The Scottish Government identified initial 24 Areas of Search (AoS) as potentially suitable for conventional and deep-water OWF locations and then updated to 17 Draft Plan Options (DPO) for future assessment (Figure 1.3). Although the planned areas for OWFs in more recent DPO decreased relative to AoS, they are still spread around Scottish waters.

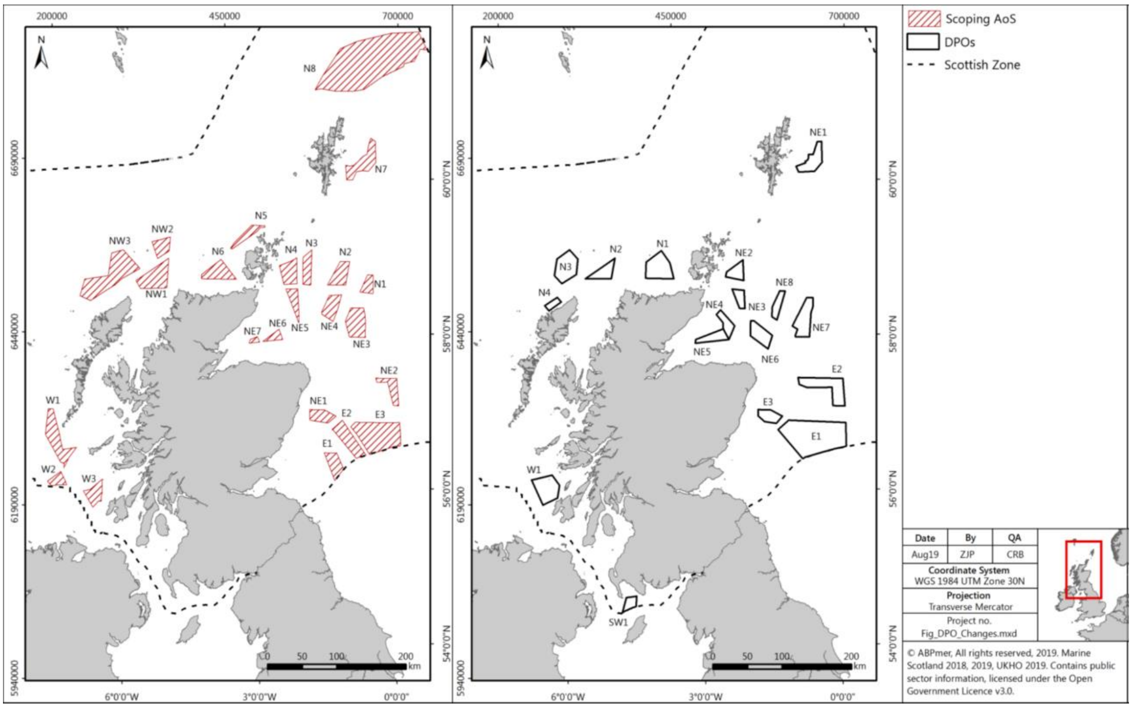

Figure 1.3 Evolution of initial AoS to DPOs (Source: Scottish Government, 2019b).

1.1.3. Seafood sector overview: Trends in fisheries and aquaculture in UK and Scotland

There are three main sectors within marine seafood production, which are fishing (i.e. capture fishery), fish processing and aquaculture. The seafood sectors are very important in the UK, where fish has always been a traditionally steady food source for households. UK household consumption of fish as a proportion of overall expenditure on food has remained around 5% (about 500 thousand tonnes) between 2008 and 2017 (MMO, 2018). UK vessels landed 698 thousand tonnes of sea fish with a value of £989 million in 2018 (MMO, 2018). Among all landings, around two thirds were caught from Scottish waters (ICES divisions IVa and VIa) (MMO, 2018), which makes fisheries particularly commercially important in Scotland. Figure 1.4 shows the distribution of demersal, pelagic and shellfish landings by the UK fleet from Scottish seas in 2016. For demersal and pelagic fisheries, important areas are located in the northern and eastern North Sea while for shellfish fishery are predominately from inshore areas.

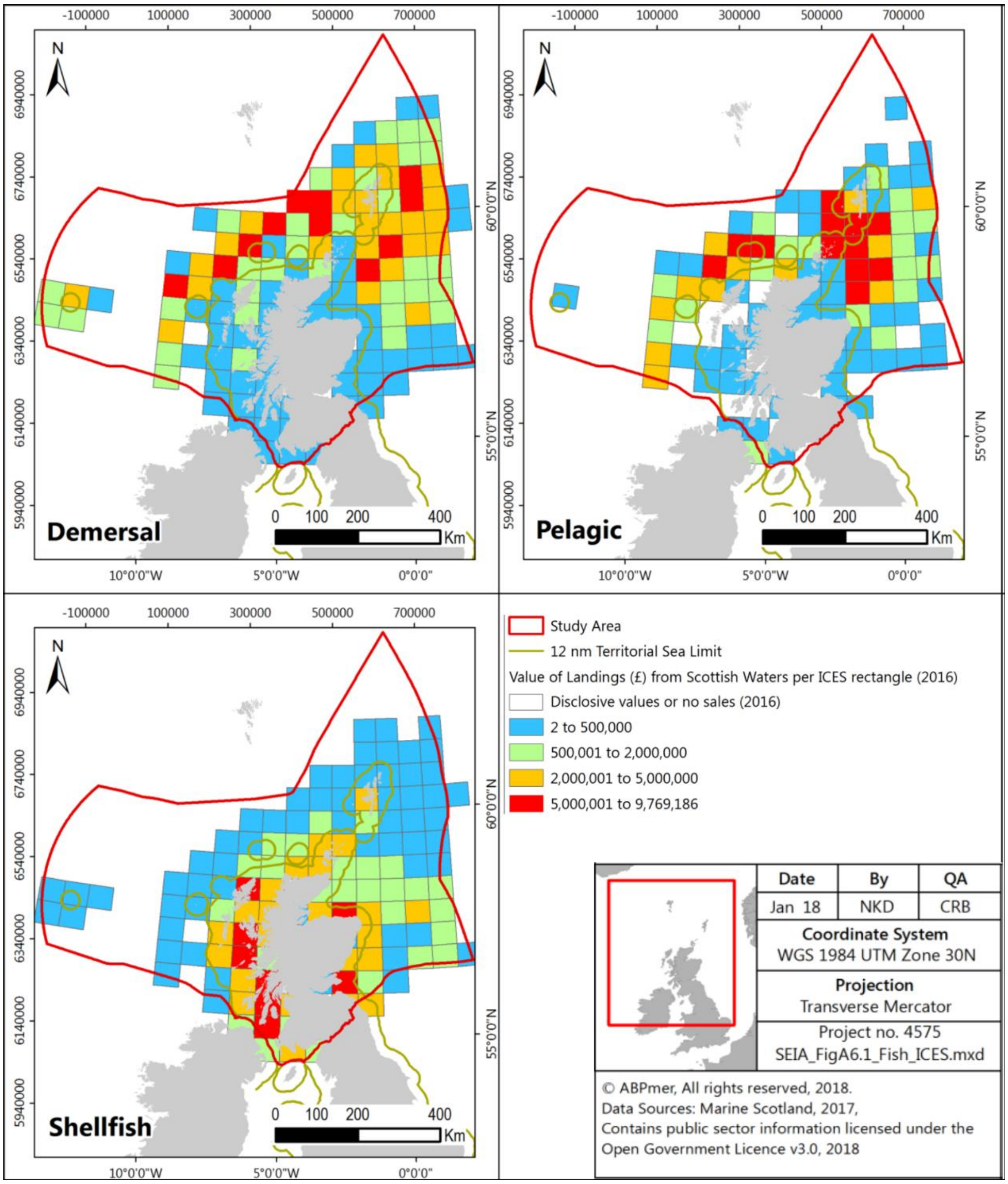

Figure 1.4 Value of demersal, pelagic and shellfish landings (£) from UK vessels in Scottish seas by ICES rectangles in 2016 (Source: Scottish Government, 2018d).

The demand for fish caught by Scottish boats is increasing both domestically and globally. Seafood was Scotland's second largest food and drink export in 2017, with an approximate export value of £944 million (Scottish Government, 2019c). The latest statistics for the Scottish marine economy showed that the fishing sector generated £316 million GVA (see Figure 1.5), accounting for 0.24% of the overall Scottish economy and 6% of the marine economy in 2017 in terms of GVA. The fish processing sector had the highest GVA among the three seafood sectors until 2017, when the aquaculture sector experienced significant growth. The historical trends for GVA are similar for the fish processing and fishing sectors, which is expected given that fish is the main production input to fish processing. In 2017, fish processing generated £392 million GVA, accounting for 0.29% of the overall Scottish economy and 8% of the marine economy in terms of GVA. With the increasing demand for seafood, marine capture fisheries have been under pressure as a result of overexploitation, quotas, rising costs such as fuel and other fishing restrictions (Neubauer et al., 2013). Therefore, there is an increasing trend in aquaculture. From 2016 to 2017, the GVA from the aquaculture sector almost doubled to £436 million, overtaking the fish processing sector as the sector with the highest GVA, accounting for 0.33% of the overall Scottish economy and 8% of the marine economy in terms of GVA. It is estimated that 40% of aquaculture seafood is currently exported (Scottish Government, 2019c). Over 95% of aquaculture production is from Atlantic salmon (Scottish Government, 2019d). There are 16 salmon-producing companies operating at 254 sites, which is far from the full potential of this industry (Scotland Food and Drink, 2016). Scotland also has plans to continue to expand aquaculture production in order to contribute to strengthening global fish supply and realise the full economic potential (Scottish Government, 2019d).

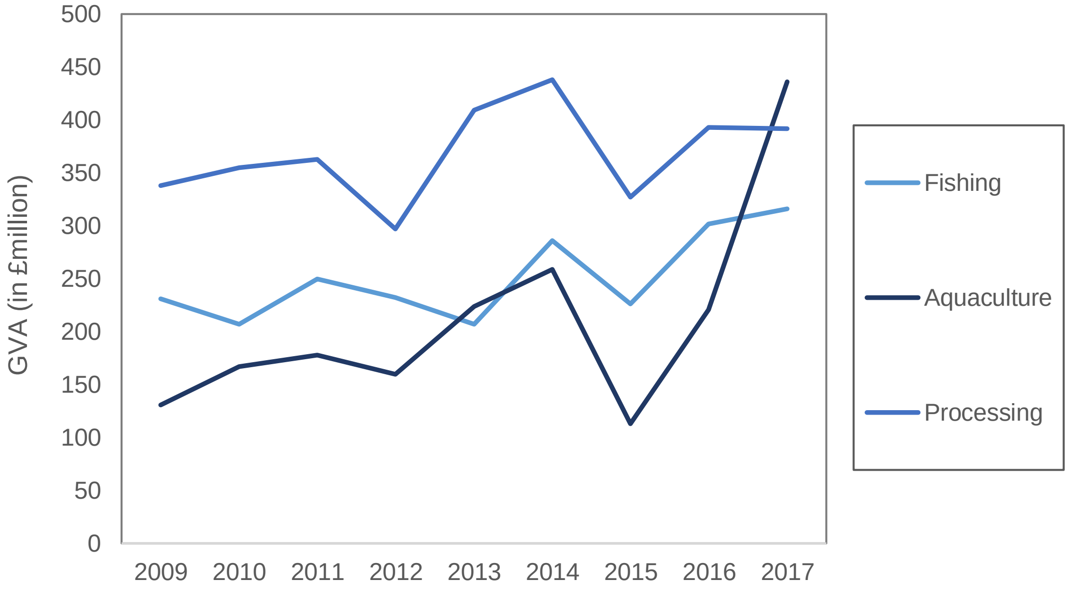

Figure 1.5 GVA (in 2017 prices) generated by fishing, aquaculture and fish processing sectors in Scotland, 2009 to 2017 (Source: Scottish Government, 2019d).

The seafood sectors operates alongside many other marine users, in waters where access to space is increasingly competitive. With the ambitions to expand both OWFs and aquaculture, the potential for conflict in the marine environment is rising, meaning that increased energy security could impact seafood supply. The economic and environmental linkages between OWFs and seafood sectors are therefore appropriate for consideration in the energy-food nexus context.

1.1.4. Economic and environmental linkages in the marine energy-food nexus

Given the complexity of the marine environment, both the nature and magnitude of the nexus linkages between offshore wind energy and seafood productions depend on a number of factors. Within the nexus framework, the linkage between nexus elements could be through macroeconomic linkages (e.g., one element serving as a production input for another or competition for limited production resources), or through environmental linkages (e.g., development in one nexus elements has ecological impacts on other nexus elements). Such nexus linkages could result in trade-offs and/or synergies between energy and food.

1.1.4.1. Economic linkages

Again, from the economic perspective, on the production side, considering ‘food’ and ‘energy’ as production inputs creates a channel through which a change in one nexus element can affect the other nexus element. For example, energy is an essential input in food production. Food production directly requires energy, and transportation and processing of food can be very energy intensive as well (Wakeford et al., 2015). Food could also be an input in energy production given that agriculture products like maize and sugarcane can be used as biofuel feedstock (Ewing and Msangi, 2009). In addition, energy and food production are competing with each other for limited productive resources: economic ones such as capital and labour, and natural ones such as land and water (FAO, 2008). Expansion in either food or energy production would inevitably shift these productive resources away from the other sector, resulting in conflicts. The recent development of biofuels is one example of a similar energy-food conflict. Many studies have investigated the trade-offs between biofuels and agriculture in terms of land conflicts (e.g. Goldemberg et al., 2008; Johansson and Azar, 2007). They showed that expansion of biofuels would cause a decrease in food production and also demonstrated a positive correlation between agricultural commodity price and energy price, mainly through the above production linkages. The expansion of offshore wind energy has similar production linkages with seafood production. Electricity is an essential production input in almost all sectors of the economy, including seafood sectors. Furthermore, there is considerable potential for competition over production factors like labour and capital such as fishermen moving out of fishing and into the OWF sector. Fishermen could share knowledge with other marine industries which can lead to innovation (Bakker et al., 2019), for example they could provide support services or surveying for the wind industry (Blyth-Skyrme, 2010).

On the consumption side, both food and energy are necessity goods for households. In the UK, energy makes up 8.1% of all household spending with electricity representing half of the household energy budget (Advani et al., 2013). Food consumed at home accounts for 18.3% of household budgets, with fish accounting for 5% of total food spending (ONS, 2019a). Through the consumption linkage, potential changes in the price of electricity generated by OWFs will affect the household's purchasing power for food. In particular, reducing the cost of OWFs may have important effects on household electricity consumption and particularly on fuel poverty in lower-income households. One previous study focusing on the UK suggested that expanding OWFs under high production cost would affect wholesale market electricity price (Green and Vasilakos, 2011). Therefore, under the current decreasing cost trend, the electricity price is expected to decrease with the increasing OWF capacity and potentially bring benefits to households. In addition, the expansion of OWFs will increase production cost of seafood sectors resulting in reducing supplies and increasing prices of seafood, which also impacts households' choices on seafood.

1.1.4.2. Environmental linkages

All the linkages mentioned above are mainly from the economic perspective, and these production and consumption linkages between OWFs and seafood production mainly represent conflicts and trade-offs within the nexus. However, further examination of the environmental linkages between OWFs and seafood production reveals conflicts and possible synergies. On one hand, OWFs and fishing activities have spatial conflict over marine spaces. Fishing activities (e.g. bottom trawling) are usually prohibited in OWFs, reducing the marine area available for fishing (e.g. Mackinson et al., 2006). Therefore, the expansion of OWFs might crowd out seafood production from limited marine areas and thus threaten seafood supply. Furthermore, Figure 1.6 shows the latest 17 new planned OWFs areas (DPO) potentially suitable for wind energy generation in Scotland, which overlap with some of the most valuable fishing areas. In particular, the North East (ICES Area IVa) landed 220 thousand tonnes of sea fish and shellfish, representing more than half of the tonnage of all landings by Scottish vessels (Scottish Government, 2019e), meanwhile this area has also most operational and planned OWFs (4641 km^2 area planned) (Scottish Government, 2019b).

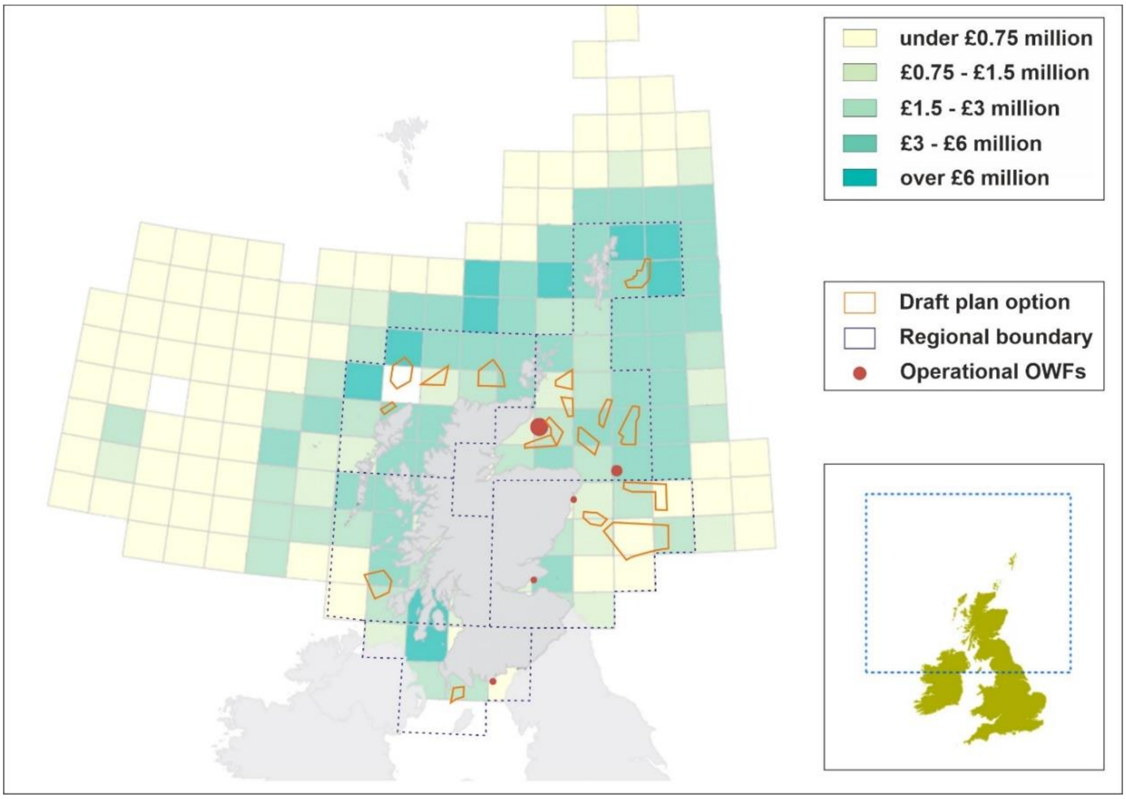

Figure 1.6 Spatial distribution of average value of all fisheries landings and the potential OWF areas for future offshore wind development in Scotland (Source: Scottish Government, 2019b, 2011).

On the other hand, wind turbine foundations may act as artificial reefs, providing shelters and habitats for certain fish species (Langhamer et al., 2009). Consequently there will be an increase in the number of fish attracted by the artificial reef effect of OWFs. Based on the definition of natural capital above, the increased fish species means positive impacts on natural capital in terms of fish stock. It further enhance the ecosystem services (i.e. harvested fish from the marine environment) the natural capital could provide. There are therefore opportunities to co-locate OWFs with fisheries to benefit from enhanced ecosystem services (Hooper et al., 2015; Hooper and Austen, 2014), and thus benefit seafood production.

These economic and environmental linkages provide significant incentives to make more efficient use of marine space, indicating that potential trade-offs and synergies from the nexus perspective should be carefully considered in marine spatial planning (MSP). MSP provides an integrated framework for balancing the existing and future marine uses (Douvere, 2008; Douvere and Ehler, 2009). As the implementation of OWFs has entered into the increasingly crowded marine environment, it is necessary to apply MSP to coordinate different marine uses. One of the major purposes of MSP is to ensure that all activities that take place in the marine space can function together in an efficient and sustainable way. Therefore, MSP could be regarded as a valuable integrated approach for mitigating the nexus in marine environment (Teisl et al., 2017).

This section introduces the current states of OWFs and seafood productions, and their economic and environmental linkages from the nexus perspective. The next step is to find out the suitable nexus assessment methods to be able to quantify the trade-offs and synergies between offshore wind energy and seafood production.

1.2. Nexus assessment

The nexus approach aims to avoid trade-offs and strengthen synergies of food, energy and water resources at economic, social and environmental scales, and guide development of cross-sectoral policy making (Albrecht et al., 2018). The FEW nexus offers a promising conceptual approach, but its application in practice requires a robust and integrated assessment tool for analysing nexus linkages as consequences of certain policies or actions to guide related management and development activities (McCarl et al., 2017). In addition to understanding trade-offs and efficient resource use, how changes in nexus elements impact on environment, economy and society should also be assessed to imply feasible policy and corporate decision making regarding the management of nexus elements (Biggs et al., 2015).

1.2.1. Nexus assessment methods

As a result of the increasing use of the FEW nexus as an analytical framework, both qualitative and quantitative assessment methods have been developed.

While qualitative methods can contextualize critical interlinkages, quantitative methods can further define the magnitude of certain changes between nexus elements and even extend to a full environmental and/or economic and/or social scope (McGrane et al., 2018; Ringler et al., 2018a). Decision makers need quantitative assessment tools to be better informed about trade-offs and synergies between different development and management choices which could help them identify options on how to manage resources sustainably (Endo et al., 2017). If significant negative impacts of a certain policy are identified through the assessment, appropriate responses should be implemented by decision makers to make adjustment to avoid the unintended consequences.

A number of methods have been developed to assess the nexus quantitatively under different scales of analysis (Albrecht et al., 2018; McGrane et al., 2018; Ringler et al., 2018a). These methods originated from the areas of environmental management, economics, indicators, statistics and integrated models (Albrecht et al., 2018). Specific tools frequently used include environmental management tools such as life cycle analysis (LCA) (e.g. Salmoral and Yan, 2018), system analysis such as system dynamic models (e.g. Cai et al., 2019), and socio-economic models such as input-output analysis (e.g. White et al., 2018). There are more environmental management than economic tools (Albrecht et al., 2018) though computable general equilibrium models are increasingly being applied in the nexus context (e.g. Ringler et al., 2018b).

Economic models have been commonly used as decision support tools for policy makers, as they attempt to analyse structures of production and consumption and the economic consequences are always stakeholders' priority (Bieber et al., 2018). However, economic interests often concentrate on short-term responses in production and consumption while ignoring the long-term sustainability. Ecosystem service valuation provides a link between the environmental and economic aspects, providing a way to convert qualitative ecosystem services into quantitative measures (Dalton et al., 2016; Hooper et al., 2017). Natural capital accounting (NCA) is being developed as a holistic tool to identify, quantify and value ecosystem services in monetary and non-monetary terms (Hooper et al., 2019; Voora and Venema, 2008). Linking NCA and ecosystem services approach with economic models offers the potential to identify and quantify the environmental impacts upon the economic indicators, the management of natural capital and the contribution of ecosystem services, which could provide a more robust framework to assess nexus interactions.

1.2.2. Reason to choose CGE models

Many economic models are available as tools for nexus assessment, such as the fixed price input-output (I-O) model, the supply-driven social accounting matrix (SAM) model, the limited scale partial equilibrium (PE) model, the computable general equilibrium (CGE) model, and the macro-econometric model such as non-equilibrium Keynesian models.

Compared to other economic models, a CGE model is chosen as the suitable nexus assessment tool in this thesis due to the following characteristics. First, a CGE model supports an integrated framework to assess the nexus linkages because all economic agents in the model are linked together through the circular flow of income and spending, allowing variations in both output and price (Burfisher, 2017). Varied prices overcome the limitation of fixed-price models like IO and SAM models which are linear models and no substitution is allowed, so that they tend to overestimate impacts (Seung and Waters, 2006). PE models could overcome some of these limitations of fixed-price models but still suffer from limited scale of assessment (Valin et al., 2014). Being non-linear, CGE models can better consider all economic agents in a wider framework, allowing varied prices and substitution effects. Varied outputs show how changes in one nexus element induce changes in other nexus elements by allocating limited resources through the price mechanism in the model. In CGE models, the resources are the constraints to be used as inputs in the production of nexus elements (Devarajan and Robinson, 2002; Robinson et al., 1999). It specifically fits the need of nexus thinking around competition over limited resources and how to allocate these resources between nexus elements to increase resource efficiency (Bazilian et al., 2011). In addition to understanding trade-offs and resource-use efficiency regarding output and price changes from production side, outcomes in terms of social equity, externalities, and socio-ecological resilience are also important in the nexus approach (Kurian, 2017). As the household sector in a CGE model can be disaggregated into different groups, the model can capture detailed distributional impacts in terms of different household categories and highlight households which are most impacted from a change in a certain nexus element. In this sense, a CGE model can therefore contribute to estimating the social impacts of energy-food provision in the nexus framework.

Second, a CGE model also has a flexible framework that can be designed to isolate the specific nexus elements as production sectors to concentrate on particular the nexus linkages depending on the specific research aims (Al-Riffai et al., 2017). As the model structure could be narrowed down to the specific nexus elements, it is a preferable starting point to analyse unknown nexus linkages, such as OWFs and seafood production. This makes the CGE model stand out of econometric models. For example, non-equilibrium Keynesian model not only requires considerable and time-series data but also has difficulties isolating the effects of individual policies from other changes and external factors (Pollitt and Mercure, 2018). In comparison, CGE models requires less historical data sets and are capable of providing more detailed sectoral and institutional results (Thurlow, 2004). Furthermore, such flexible structure is useful to extend its assessment scale. For standard CGE models, only those linkages that can be translated into economic changes through the market economy can be directly traced in CGE models to determine the effects of the representative agents (Bosello et al., 2012). Some environmental impacts (e.g. impacts on fish stock due to artificial reef effect) cannot be directly implemented in a standard CGE model because such impacts may not cause direct economic impacts. Flexible CGE model structure allows nexus elements introduced as ecosystem services and corresponding natural capital into the model by linking an external biological or ecological function to be used as production inputs in a CGE model structure (e.g. Allan et al., 2018; Jin et al., 2012). To do so enables comprehensive analysis of the two-way interrelationship between the economy and the environment in the energy-food nexus. Such an extended CGE model can therefore provide insight not only at the economic and social level but also at the environmental level.

There are certain key steps in assessing the economic implications of the energy-food nexus using a CGE model for the marine environment with a specific focus on OWFs and seafood production. First, both offshore wind energy and seafood production should be independent in the economy to highlight their interlinkages. Then, the impacts of OWFs on fishing activities need to be identified and converted into marketable transactions. These changes later need to be transformed into economic variables and applied to either the production or consumption activities in the CGE model. When offshore wind energy expands, productive resources (i.e. labour, capital and marine areas) are expected to be taken up by OWFs, resulting in increasing competition for these resources. Eventually, the CGE model would reach a new equilibrium condition through the price mechanism, fitting the supply of resources to equal demand by different sectors. In addition, the nexus element of natural capital derived ecosystem services that are directly used need to be incorporated as inputs in the production of energy and food, so that their changes are endogenously included in the model. This involves conceptualization of the valuation of natural capital and ecosystem services, and determination of how to represent these values within the context of the model. Through such developments within a CGE model, not only could the impacts of economic changes on the use of nexus elements be assessed, but also the impacts of changes in nexus elements on natural capital could be quantified.

In summary, a CGE model is able to present a preliminary evaluation on the unknown nexus linkage since it could isolate effects of individual policies and provide a comprehensive interpretation about the nexus linkage at the macroeconomic scale. It allows assessment of the impact of alternative nexus strategies on sectoral changes of production sectors, on distributional effects and welfare on households, and on the overall economy, from economic and environmental perspective. These are all important factors for government and thus a CGE model could support policy development. Therefore, the CGE model is the preferential choice for nexus assessment in this thesis.

1.3. Objectives and research questions

As the previous sections have shown, assessments within a marine energy-food nexus framework could help resource management by identifying and reducing the trade-offs and reinforcing the synergies to find the best solutions for policy development and to support MSP. Given that the Scottish Government has ambitious targets for renewable energy and massive marine resources, Scotland is an appropriate case study to focus on the nexus between offshore wind energy and seafood production by developing a CGE model specific for Scotland.

The energy-food nexus involves linkages and interconnections on different levels, making it necessary to integrate economic and environmental assessment to examine the potential impacts of the development of OWFs. Therefore, the first and methodological objective of this thesis is to develop an integrated modelling framework for nexus assessment that is able to capture the relevant linkages of the marine energy-food nexus. As will be reviewed in Chapter 2, existing literature of OWFs and fisheries is focussed on either the environmental impacts or the macroeconomic impacts separately and most are qualitative impact assessments. An integrated and environmentally-extended CGE model working on different levels of the economy and the environment is built in this thesis, to fill an evidence gap by providing a quantitative assessment of the impacts of OWFs on seafood production from the energy-food nexus perspective.

The second and empirical objective of this thesis is to identify and assess the economic and environmental linkages between offshore wind energy and seafood production, which can help maximize synergies and minimize trade-offs within the energy-food nexus. The holistic modelling framework is developed to assess the economic, environmental and social impacts of the expansion of OWFs on seafood production. The model results should be able to provide quantitative macroeconomic insights on energy security and fish supply, on distributional effects across different households, and on the overall economy. Furthermore, the model in this thesis is made more practical as it can measure both the potential spatial conflicts and the synergies between offshore wind energy and seafood production, which is essential to consider sustainable use of natural resources in the marine environment.

The last objective of this thesis is to consider the policy implications of model results. As a macroeconomic model, a CGE model could provide quantitative analysis of the overall economy, which could be used to inform policy making. For example, the model could run scenarios under different cost of OWFs to test the validation of CfD schemes for developing renewable energies; the distributional effects across households could be used to evaluate if renewable energy would exacerbate or mitigate fuel poverty. The environmentally-extended model structure allows policy implication to MSP and sustainable marine environment.

Based on the three objectives of this thesis, there are three research questions that correspond to different areas of the energy-food nexus to provide a more holistic assessment of the nexus. The questions are listed below.

The first research question highlights the trade-offs between offshore wind energy and seafood production sectors.

(i) How does the offshore wind energy expansion affect energy security and fish supply from economic and environmental perspectives?

To be more specific, this research question is divided into three sub-questions, of which the first two concern the macroeconomic linkages whereas the third focuses on the environmental linkages:

a. How does offshore wind energy expansion affect energy security through electricity availability and affordability?
b. How does offshore wind energy expansion affect fish supply through seafood availability and affordability?
c. What are the feedbacks between impacts of changes in natural capital on economic performance and the impacts of economic changes on the state of natural capital?

The second research question addresses distributional effects across households as the social dimension of the nexus perspective:

(ii) How does the expansion of offshore wind energy affect households?

Based on different household income levels, the assessment of household impacts could be further divided into three sub-questions:

a. How do households' incomes change?
b. How do households' consumption patterns change?
c. How does household welfare distribution change?

The third research question is the application of the model results:

(iii) What policy implications would the model results have?

Depending on the aim of this model, there are again three sub-questions to be addressed:

a. What do the model results imply for energy-food nexus in the marine context?
b. What are the lessons for other developing marine renewables?
c. What are the implications for marine spatial planning?

In conclusion, answering the three research questions and their sub-questions would explicate the nexus linkages between offshore wind energy and seafood production covering three dimensions of sustainability: environmental, economic, and social.

1.4. Structure of the study

This thesis follows the outline below, which is illustrated schematically in Figure 1.7. Chapter 2 reviews the literature on (i) the environmental and economic linkages between OWFs and fisheries from the nexus perspective, which demonstrates the necessity to make quantitative macroeconomic assessment; (ii) CGE model applications to marine renewable energy, fisheries, the energy-food nexus, and natural capital, which highlights the gaps in knowledge and justifies the use of a static CGE model as the most appropriate way to assess nexus linkages. This is followed by the methodology (Chapter 3) which first explains the general CGE model framework and then further describes the Scottish Economy Marine Model (SEMM) structure developed specifically for this thesis and the two innovative modelling extensions developed in order to better assess the energy-food nexus. Chapter 4 is the results chapter presenting the model results corresponding to the basic model structure and its two additional modules. The basic model structure explores the macroeconomic linkages between OWFs and seafood production on the energy-food nexus in Scotland by comparing scenarios with higher and lower cost of OWFs. The first novel marine resource allocation module that further examines the physical environmental linkage of conflicting use of marine resource between massive expansion of OWFs and fishing activities. The second novel module and examines the impact of OWF expansion on ecosystem services and natural capital, and in turn the wider economy. Chapter 5 is the discussion chapter which highlights the methodological advances, brings together the main findings across the three individual results chapters, and discusses the policy implications of the model results. Finally, Chapter 6 provides a brief conclusion of the whole thesis and highlights again the contributions that have been made. In addition, the model structure, including all parameters and equations are contained in the Appendix 1 and one example of calibrations in the model is presented in the Appendix 2.

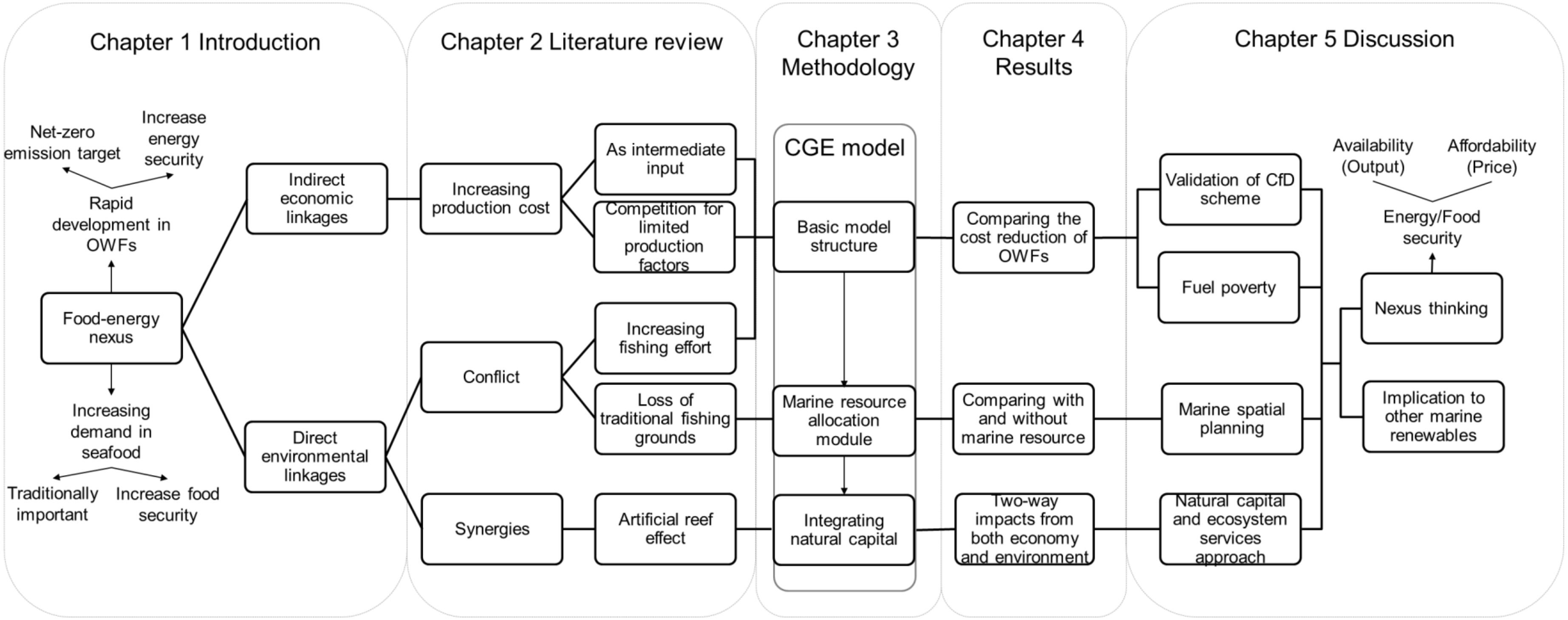

Figure 1.7 Schematic flow chart of this thesis to illustrate the main contents in each chapter

2. Literature review

This chapter 2 reviews a range of research which can contribute to the advancement of nexus thinking. Offshore wind farm (OWF) development and its impact on fisheries is used as the organising feature within the review but papers employing the nexus approach from a variety of different applications are also heavily used. Economic and environmental perspectives are specifically considered including environmental linkages (i.e. conflicts and synergies), ecosystem services and natural capital approach, wider macroeconomic impacts, and macroeconomic linkages within the nexus approach. Therefore, Section 2.1 identifies a knowledge gap in assessment of the quantitative impacts of OWFs on fisheries and thus seafood production from a macroeconomic perspective. Section 2.2 then reviews a sample of CGE model applications. Literature focusing on the assessment of individual sectors (i.e., marine renewables, fisheries) as well as energy-food nexus linkages (i.e., agriculture and biofuel) provide useful insights into the characteristics of economic variables, the complexity of the systems and the gaps to be filled when developing a macroeconomic model to assess the economic impacts of alternative resource management options. A comparison between the reviewed static and dynamic CGE models is found at the end of Section 2.2, which highlights the reason for selection of a static CGE model in this thesis.

2.1. Review of the overall environmental and macroeconomic impacts of offshore wind energy

The UK Offshore Wind Industry has seen a period of significant growth in the past decade, growing from 951 MW in 2009 to 10,141 MW in 2019 (Table 1.1), an almost 970% increase in 10 years. It is likely that OWF deployment will continue to increase rapidly given its potential to reduce carbon emissions and increase energy security (Rodrigues et al., 2015). On one hand, OWFs could bring economic benefit through increasing employment and investment. The economic consequences of offshore wind energy are of significance to policy-makers since economic growth is typically one of the wider goals of government policy (Allan et al., 2015). On the other hand, there are potential trade-offs between OWFs and seafood production through direct environmental linkages (e.g., changing fish availability) or indirect macroeconomic linkages (e.g., reallocation of production factors). These links will further impact on food through wider production and consumption processes.

2.1.1. The direct impacts on seafood production through environmental linkages

There are direct impacts on fishing activities from the environmental effects of the expansion of OWFs. Through the environmental linkage, the fishing activities are obstructed by OWFs and thus the supply of fish. Changing fish supply further influences the whole seafood production and the wider economy through the macroeconomic linkages. Reviews of the broad environmental impacts of OWFs can be found within the literature (e.g. Bailey et al., 2014; Bergström et al., 2014; Snyder and Kaiser, 2009), but the following sections focus mainly on empirical assessments of the environmental effects of OWFs on commercial fishing activities and fishery species in northern European marine waters, where most OWFs development has occurred (WindEurope, 2019). The review in the following section is divided into two parts: (i) the conflicts and (ii) the synergies between OWFs and fisheries, considering impacts on both commercial species and fishing activities.

2.1.1.1. Conflicts

The presence of OWFs will directly influence marine species. The construction phase would have impacts on fish and fishing activities through amongst others underwater noise, and vibration of dredging and pile-driving (Gill et al., 2012; Thomsen et al., 2008). During the operational phase, further potential negative impacts caused by noise (e.g. Wahlberg and Westerberg, 2005) and the electromagnetic fields (EMF) (e.g. Öhman et al., 2007) may disturb fish and other species living around the OWF areas, although current evidence suggests this is of minor importance (Gill et al., 2012; Vaissière et al., 2014; Westerberg and Lagenfelt, 2008).

Even though there is a lack of empirical evidence of negative effects on most commercial seafood species, there are documented negative impacts on fishing activities. Potential loss of access to traditional fishing grounds is the principle direct conflicts between OWFs and fisheries. Although OWFs location choices require consenting processes that consider existing fishing activity, OWFs development areas still inevitably overlap with fishing grounds (Mackinson et al., 2006). For safety reasons, some countries, such as in Belgium, prohibit fishing across all vessels within OWFs (Coates et al., 2016). Some studies have proved large reductions in fishing activities due to replacement of fishing grounds to areas closed by OWFs. It has been estimated that the gillnet fishery within the North Sea German EEZ could lose up to 50% in landings when OWF areas are closed entirely to fishing (Stelzenmüller et al., 2016). A further study in Germen suggested that significant fishing opportunities of flatfish would be lost (e.g. 31.6% for dab, 52.8% for sole, 19.5% for brill, 40.2% for turbot and 36.8% for plaice) to fishermen due to the closure of OWF areas (Berkenhagen et al., 2010). The potential loss of access to traditional fishing grounds, which would lead to increased competition, conflict and escalating fuel costs was identified as a major concern (Mackinson et al., 2006).

Even without such legislation prohibiting access in the UK, disruption to fishing activities has still occurred following the development of OWFs (e.g. Hooper et al., 2015; Mackinson et al., 2006). In one of the few studies that includes secondary data from fish landings and vessel monitoring systems as well as primary data from questionnaires, Gray et al (2016) found that fishing activity declined in five OWF sites in UK following the construction. However, since fishermen do not complete loss or have restricted access to fishing grounds in UK, the actual impacts of OWFs on fishing activities would be displacement of fishing effort depending on fishermen's gear type and attitudes towards OWFs. Literature regarding fishermen's attitudes on OWFs and the impacts on their fishing effort is based primarily on interviews, questionnaires and workshops. These are derived mostly from Scotland and the wider UK, with additional information from European waters. The Mackinson et al (2006) study demonstrated that smaller (<10 m) fishing vessels were reported to be most impacted ones as no alternative fishing grounds for them. Effects varied depending on the gear type: those fishing with mobile gear (particularly bottom trawls) were impacted more than static gear (such as pots) since there was no adequate space between turbines to deploy the mobile gear and snagging cables (Mackinson et al., 2006). Fishermen reported their concerns about continuing to fish within OWFs were primarily related to loss or movement of gear, disturbance to their fishing effort during OWF construction and maintenance and safety issues including fishing gear getting trapped by cables or fishing vessel breakdown leading to turbine collision during fishing (Alexander et al., 2013a, 2013b; Gray et al., 2016; Hooper et al., 2015; Reilly et al., 2015). Besides fishermen, interviews with relevant stakeholders reported their concerns of the impact on the Scottish fishing industry since they were often overlooked during the process of OWFs development in Scotland (O'Keeffe and Haggett, 2012).

The above literature about OWFs impacts on fishing activities is mostly qualitative. There are very few quantitative assessments regarding impacts of fishing effort displacement and even the cumulative impacts across the whole economy. Trade-off analyses coupled with biological-economic modelling has been undertaken, which demonstrated that different fisheries respond differently to the installation of marine renewable energy, including offshore wind (White et al., 2012). The relationship between OWFs and fisheries was represented as a negative-sloping convex curve, which indicated non-linear trade-offs. The study also found out that the trade-off was more severe for certain fish species (i.e. flounder) because flounder compete with offshore wind energy infrastructures for soft-bottom habitat (White et al., 2012). Yates et al (2015) also observed similar non-linear trade-offs between fishing activity and renewable energy sites based on interviews with Northern Irish fishers. They also found that increased offshore renewable energy affected different sectors within the fishery industry, i.e. pot fishing experienced least reduction in fishing value while scallop suffered more and Nephrops the most. The above two quantitative assessments stay at impacts on fishing activities, ignoring the subsequent impacts across the wider economy.

2.1.1.2. Synergies

The implications of OWFs for fishery species are not necessarily negative. OWFs developments introduce structures that provide increased shelter and colonisation substrates for many marine organism (Bergström et al., 2013). Increased abundance of commercial seafood species close to OWF foundations has been observed in several studies across European waters, including for swimming crabs, brown shrimp, pouting, whiting, cod, bullrout, velvet crab, dab, sandeels, and blue mussels (Bergström et al., 2013; Degraer et al., 2015; Langhamer et al., 2009; Langhamer and Wilhelmsson, 2009; Maar et al., 2009; Reubens et al., 2013; Stenberg et al., 2015; van Hal et al., 2017; Wilhelmsson et al., 2006; Wilhelmsson and Malm, 2008). All these previous studies provide a vast amount of data on environmental effects at the species or community scales with the general conclusion that the artificial reef effects of OWFs are sufficient enough to attract some of commercial fish species. However, the scale of benefits to fisheries from these aggregations is not well studied, and may be limited as increased abundance was mainly observed close to turbines foundations, which only cover a small amount of the total OWF area (Bergström et al., 2014).

As not all fishing gears would be excluded from OWF areas, certain fishing activities could co-locate with OWFs and benefit from artificial reef effect. In particular, static fishing gear is more acceptable for use within OWFs than mobile gear (Jongbloed et al., 2014). Evidence from ecological surveys of OWF foundations suggest that crab in particular occur in sufficient numbers to potentially support co-location (Hooper and Austen, 2014), and careful construction of the turbine infrastructure may increase the yield of both crab and lobster (Christie et al., 2014). In practice, examples were found where fishing activities co-exist with OWFs in the UK (Gray et al., 2016). From the social perspective, stakeholders were generally accepting of the co-location in principle as an opportunity for sustainable, resource-efficient solutions for combined ocean use (Wever et al., 2015), although, as noted above, fishermen had a range of safety concerns (Hooper et al., 2015).

Besides capture fisheries, OWFs could also co-locate with aquaculture sites as an alternative multifunctional utilisation of offshore areas and its sustainable development (Buck et al., 2004), for example through mussel farming or seaweed cultivation (Fayram and de Risi, 2007). The artificial reef effects caused by the hard substrate of OWFs could be positive for aquaculture as species are attracted near turbine foundations, supporting the productivity of additional aquaculture efforts (Langhamer, 2012). A GIS modelling framework combined with environmental criteria evolution techniques (e.g. temperature, salinity or oxygen) showed that several wind farms were *de facto* suitable sites for aquaculture since they exhibited high suitability scores based on the criteria (Gimpel et al., 2015). An analysis was made of available ocean space that highlighted the potential to further develop aquaculture and OWFs in Baltic and Norwegian Sea as these areas meet the geographic criteria (van den Burg et al., 2019).

Although the above studies implied that co-location between OWFs and fishery activities is feasible, the establishment of co-location would need appropriate marine spatial planning (MSP) to better coordinate the multiple uses of the marine area (Christie et al., 2014; de Groot et al., 2014; Jongbloed et al., 2014; Pınarbaşı et al., 2017; Stelzenmüller et al., 2016). The literature reviewed identified a number of key issues that to date hinder an actual implementation of co-location as a possibility in the MSP process: appropriate assessment of fishing effort displacement by OWFs, appropriate legal and insurance frameworks, and careful design of the location. In particular, a socioeconomic assessment with regards to impacts of OWFs should be done as quantitative analysis is an important factor in the consideration process for policy-makers to make decisions on MSP (Christie et al., 2014).

In conclusion, the development of OWFs replaces the existing fishing grounds by obstructing fishing access and navigation routes, and even where access is still possible, fishermen are often reluctant to deploy gear in OWF sites and thus have displacement of fishing effort. These effects could increase the cost of fishing activities so that fish supply reduces. However, OWFs would have potential to increase fish stocks due to artificial reef effect, which benefits the fishing activities. The implications of impacts of OWFs on fishing activities could translate into changing fish supply and prices, and therefore the seafood production cost, which would change the food affordability and eventually fish supply in the energy-food nexus. Therefore, there is a need to translate the above reviewed environmental impacts into socioeconomic impacts to have a holistic understanding of the economic, social and environmental impacts of the rapid expanding OWFs from an energy-food nexus perspective. To better make the socioeconomic assessment, the natural capital and ecosystem services approach should be applied as it considers the impacts of OWFs in a more holistically integrated socioeconomic-ecological framework.

2.1.2. The impacts on ecosystem services and natural capital

The ecosystem service approach focuses on the interactions between environment and human well-being (Fisher et al., 2009). Ecosystem service is a wide range of goods and services provided by natural capital as the concept of the stock of natural resources (UK NEA, 2011). As defined in Section 1.1, food and energy are known as provisioning ecosystem services as inputs to the economic production, which is provided by natural capital as an important asset in the environment. The ecosystem services approach therefore links economy with environment in a socio-ecological system where nature and society are capable of enhancing their roles mutually (Fürst et al., 2014).

The above reviewed environmental impacts of OWFs on fish species and fishing activities could be interpreted in natural capital and ecosystem services approach. It has been reviewed in Section 2.1.1.2 that the artificial reef effect increases ecosystem services like habitat heterogeneity (supporting ecosystem services), supports food webs (regulating ecosystem services) and eventually show as increase in fish biomass (provisioning ecosystem services) (Mangi, 2013). Biomass increased within OWF areas would increase the productivity of the fish species and further sufficiently benefit the fishing activities near OWF areas as the spillover effect (Gell and Roberts, 2003; Goni et al., 2008).

As production inputs, ecosystem services would bring benefits to economy, which can be valued in monetary terms (NCC, 2017). The monetary valuation of ecosystem services allows impacts to be reported in a single metric which can support the use of quantitative assessment tools (Hooper et al., 2017), such as CGE model in this thesis. Furthermore, the modelling framework would help interpret the monetary valuation of ecosystem services by permitting the magnitude of impacts to be integrated into decision making process (Fürst et al., 2014). Ecosystem approach could also help promote MSP decisions to cover effective implementation of ecosystem management frameworks in planning processes and focuses on achieving sustainable management of marine resources (Domínguez-Tejo et al., 2016). Besides, there is growing attention on natural capital accounting which also aims at better inform policy decisions on sustainable use of marine resources (Hooper et al., 2019; Ruijs et al., 2018). Natural capital accounting is a framework covering both the ecological and socioeconomic aspects, to support understanding the importance of deterioration of natural capital and the implications for future growth (NCC, 2017). Given that natural capital provides valuable ecosystem services used as inputs to economic production, maintaining natural capital is essential for sustainable flows of ecosystem services in the future. The establishment of natural capital accounting frameworks aims to promote sustainable development by ensuring that natural resources are mainstreamed into development planning and national economic accounts. There are international programmes to develop natural capital accounts like SEEA (UN et al., 2014), implemented, for example, through national accounts in the UK (ONS, 2019a), and regional accounts in Scotland (Scottish Government, 2019f). Combining the natural capital accounting and valuation of ecosystem services approaches moves step further of the environmental impact assessment of OWFs towards socioeconomic level, which accounts for transactions between economy and environment. Integration of natural capital and ecosystem services into quantitative modelling could be used as a tool for natural resource and environmental management (UN et al., 2014).

In addition to the above mentioned provisioning ecosystem service, qualitative descriptions of impacts of OWFs on ecosystem services have been provided by some studies (e.g. Busch et al., 2011; Hooper et al., 2017; Mangi, 2013). Meanwhile, quantification of ecosystem services and natural capital would support the evaluation 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), which is still lacking regarding the OWFs impacts on ecosystem services and natural capital. The existing quantitative assessments of OWFs are mainly focus on macro-economy.

2.1.3. The impacts on economy

Macroeconomic studies are essential for renewable technologies to provide justification for government support for the sector, as well forming a key input to corporate decision making and strategic energy system planning (Dalton et al., 2015). Given the importance of the sector, some macroeconomic analyses of offshore wind energy on the economy as a whole have already been undertaken, mostly focusing on the impacts on employment, export and gross domestic product (GDP) or gross value added (GVA) created by offshore wind energy. The studies for UK and Scotland have been concluded in Table 2.1. All of studies have shown that developing OWFs would bring economic benefits to the system-wide economy, by increasing both GDP/GVA and employment. The scale of the economic benefits is a bit different across studies, which heavily depends on scale of OWFs expansion and the method they use.

However, most of these existing studies only focus on the impacts at macroeconomic level, only two works (Fraser of Allander Institute, 2014, 2017) mention sectoral impacts but at highly aggregated level. A more holistic approach is required that explicitly considers macroeconomic linkages at both macroeconomic level and sectoral level since there are trade-offs between offshore wind energy development and seafood production through macroeconomic linkages that are omitted in the above sector specific approaches. These sectoral impacts on seafood productions through macroeconomic linkages are therefore encompassed under nexus thinking.

Table 2.1 Review of studies of macroeconomic assessment of OWFs

Study	Type of model	Results				
		Year	Capacity	Macroeconomic variables	Number of jobs	Other results
Cebr, 2012	Multiplier model	2020	33 GW	0.4% GDP increase	97,000	Annual 1% increase of GDP with 3.4 GW pa increase
		2030	49 GW	0.6% GDP increase	173,000	
Cambridge Econometrics, 2012	Macro-econometric model (MDM-E3)	2030	36 GW	0.8% GDP increase	70,000	Electricity price would be 1% higher compared to gas plants
McNeil et al., 2013	Review published works	2020	18 GW	n.a.	1.27 to 2.41 jobs per MW of new installed capacity, with a median average of 2.13	
Fraser of Allander Institute, 2014	Input-Output model	2020	8 GW	£2.2bn GVA	48,487	An increase in output for the total economy
			15 GW	£5.5bn GVA	120,658	
Catapult, 2017	Cost-benefit analysis	2030	32% UK content	£1.8bn GVA per GW installed	n.a.	n.a.
			65% UK content	£2.9bn GVA per GW installed		

Table 2.1 Continued Review of studies of macroeconomic assessment of OWFs

Study	Type of model	Results				
		Year	Capacity	Macroeconomic variables	Number of jobs	Other results
Cambridge Econometrics, 2017	Employment model	2032	13 GW	n.a.	60,000	n.a.
Crown Estate Scotland, 2018 (floating OWFs)	Excel-based economic model	2050	10 GW	£33.6bn GVA	17,000	A return of £15 for each £1 invested in early stage support.
Fraser of Allander Institute, 2017 (Neart Na Gaoithe project)	Input-Output model for Scotland	Over the lifetime	450 MW	£827.4 million GDP	13,900	Service sector has biggest GDP impact (£440 million increase)

2.1.4. The indirect impacts on seafood production through macroeconomic linkages

While the studies described above demonstrate high-level macroeconomic benefits, there are likely to be further effects on specific economic sectors affected by OWFs expansion. In particular, OWFs are expected to impact on fisheries, but these specific macroeconomic linkages have been ignored in studies to date. Energy plays an important role in food production through the macroeconomic linkages as it is a production input and competes for production factors. Literature that considers this energy-food nexus relationship mostly concerns biofuel and agriculture, which is therefore used as an example to explain what kind of potential macroeconomic linkages may exist between OWFs and seafood production.

Energy and food have two nexus linkages on the production side. The first one is intermediate input linkages that energy is an important production input for the food sector, which accounts for roughly 32% of global energy use (FAO, 2011). Zilberman et al. (2013) reviewed some empirical studies suggesting that changes in energy price would change food production costs, even though their relationship depends on many factors like location, the food and fuels considered, the modelling specification, and the time dimension. The second one is production factor linkages that energy and food production compete for limited productive resources (e.g. Hochman et al., 2012)., such as economic production factors like labour and capital, or natural resources like land. In particular, many studies recognise that agricultural production is affected when large land use competition arises between food commodities and biofuels. (e.g. Dunn et al., 2013; Rathmann et al., 2010; Valin et al., 2015). Therefore energy price will tend to affect food prices of all agriculture commodities as that rely on the same resource base (FAO, 2008). Such energy-food nexus linkages are examined in detail in one global analysis, which showed that the 35% to 40% rise in food prices during 2002 to 2008 was partly (25 – 30%) explained by higher energy prices but mainly (70 – 75%) influenced by development of biofuel (Mitchell, 2008).

There are similar production linkages between offshore wind energy and seafood production. For seafood production, the most important energy input for modern industrial fisheries is fuel (for the boats) which typically accounts for between 75% and 90% of total energy inputs (Tyedmers, 2004). Furthermore, Pelletier et al. (2014) pointed out the scale of impact on seafood production depends on the energy intensity in the production, mainly relevant to different gear type, fishing vessels and distances.

Therefore, whilst electricity is an essential production input for seafood sectors, it is not at levels that are as significant as fuel. Shifts in land use away from food production could also be applied to seafood production that OWFs would also take up marine areas away from fishery activities or would make fishermen reluctant to fish inside due to safety concerns (reviewed in Section 2.1.1.1).

Beyond these production side effects, changes in the energy price have potential impacts on the households who may switch their food consumption as can be seen from agriculture-biofuel research. Food price would increase due to lower supply and increased production cost by the development of biofuel as mentioned above, which refers to lower households' purchasing power through increasing food prices (FAO, 2008; Hartley et al., 2019). Conversely, several studies have shown that development of biofuel can provide employment opportunities and increase household income, especially for urban households (e.g. Goldemberg et al., 2008; Havlík et al., 2011; Openshaw, 2010). Ewing and Msangi (2009) further confirmed that increased income would improve purchasing power and further decrease vulnerability to price shocks for food. Such positive response to food demand would in turn increase the need in food supply so that the food demand and supply reach a new economic equilibrium level. Similar consumption-side implications could be expected in the relationship between OWFs and seafood.

In conclusion, Section 2.1 reviews the environmental and economic linkages between OWFs and seafood productions from the nexus perspective. The reviewed environmental impacts are mainly qualitative assessments. Only few quantitative works have done the trade-offs analysis using biological-economic modelling between OWFs and fisheries, but lack of the wider economic impacts. The other existing macroeconomic assessments of OWFs purely focus on their macroeconomic variables, such as GDP and employment. Even less is known about quantitative impacts of OWFs on seafood productions through the macroeconomic linkages from the nexus perspective. An integrated macroeconomic model is therefore needed to understand both the environmental and macroeconomic linkages of the rapidly expanding OWFs on seafood productions and the wider economy. The model should be able to evaluate the trade-offs between offshore wind energy and seafood production reflected in different decision making options, which can support policy makers in developing policies that are as cost-effective as possible given limited resources. As stated in Section 1.2, the thesis choose the CGE model to do the assessment. The next section reviewed literatures regarding the existing applications of CGE models on energy-food nexus.

2.2. Review of CGE model application

A CGE model is an economy-wide model that captures the interactions between all markets and economic agents. It is able to analysis the behaviour of supply and demand through the price adjustment mechanism to reach equilibrium condition. CGE models have been widely used to assess the macroeconomic impacts of environmental policy and natural resource management issues (as reviewed by Bergman, 2005; Wing, 2011). The purpose of reviewing the wide range of CGE applications is to address the capacity of CGE models to assess the nexus linkages. Relevant models that are identified to advance the research undertaken in this thesis are described in more detail below, and key information about the model description, purpose, scenario settings and geographical scope, as well as the model results, are summarised in Table 2.2.

2.2.1. Application to energy-food nexus

CGE models have been widely used to evaluate the energy-food nexus in the context of biofuel and agriculture at both global and regional scales (see the review by Kretschmer and Peterson, 2010; Nkolo et al., 2018). The expansion of biofuel would shift productive resource away from agriculture and thus impact on the food output and price which is evaluated in CGE models through the macroeconomic linkages as reviewed in Section 2.1.4. Furthermore, one of the advantages of CGE model is the resource allocation that land use characteristics could be taken as production factors to be competitively used by energy and food sectors in a CGE model, which representing the land trade-offs between biofuel and agriculture production (Kretschmer and Peterson, 2010). There are wide range of CGE models applied for biofuel issues to analyse the competition for land with agricultural crops, at global scale (e.g. static models by Banse et al., 2008; Hertel et al., 2010; dynamic models by Al-Riffai et al., 2017; Kretschmer et al., 2009; Timilsina and Mevel, 2013), and at regional scale (e.g. Ferreira Filho and Horridge, 2014 for Brazil; Gebreegziabher et al., 2013 for Ethiopia; Hartley et al., 2019 for Mozambique). Therefore, some CGE models have been reviewed below as examples of how a CGE model assess the macroeconomic impacts in the energy-food nexus issues.

In order to represent conflict use of land due to expansion of biofuel production, it is desirable to have the factor land and land conversion in an explicit way in CGE models. The general conclusion focusing on food and energy security concluded from CGE model results of expansion in biofuel is that energy security would increase whereas the number of food-insecure people would also increase by directly increasing global agriculture price and indirectly effect processed food (Ringler et al., 2016). A global static CGE model illustrated that increase in biofuel demand in EU had strong negative impacts on agriculture, which were manifest as higher global prices of agriculture products (Banse et al., 2008). At global scale, the negative impacts on agriculture supply would be moderate but it would be more significant at local scale (Timilsina et al., 2012). A regional dynamic CGE study in Tanzania found that developing biofuel would cause reduction in production of certain other crops and increase in food prices, which happened to some individual farmers but not significantly at country level (Arndt et al., 2012). Both global and regional studies show that it is important to concentrate at the regional scale as the impacts could be significant to a certain region where there is expansion in biofuel, which implies the importance of analysing the nexus linkage between OWFs and seafood production at the country level in Scotland.

All these CGE models for biofuel and agriculture nexus linkages include a specific land allocation module to represent the competitive use of land between biofuel and agriculture. The main driver of the negative impacts on agriculture is that expansion of biofuels would shift land away from agriculture, resulting an increase in biofuel land use and thus higher production cost for agriculture due to less available and more expensive land. There are different approaches for land allocation module. The simplest approach is to treat land as a homogenous factor of production in the agriculture and biofuel sectors that is fixed in supply (e.g. Kretschmer et al., 2009). The next approach is allowing land to be transformed to different uses under a constant elasticity of transformation (CET) function, introducing more detailed representation of the land as input factor (e.g. Hertel et al., 2010). Furthermore, the CET structure can be rendered more complex by nesting levels in production side, allowing more flexibility of land reallocation across different land uses (e.g. Banse et al., 2008). The different approaches of land allocation module show the flexible structure of CGE model to be capable of quantitatively assessing the similar limited resource trade-offs in an energy-food nexus. The above mentioned land use reallocation module approaches are indicated for similar marine resource allocation between OWFs and seafood sectors, where no CGE model has been applied on this issue yet.

2.2.2. Application to marine renewable energy

There are examples of the use of CGE models for macroeconomic analysis of renewable energy (as reviewed by Babatunde et al., 2017), but little attention has been paid on their use to assess the sectoral, especially seafood sectors, and overall macroeconomic impacts of offshore wind energy. At the UK level, Lecca et al (2017) used a dynamic CGE model (UKENVI) and found that 30% reduction in levelised cost would result in 0.03% to 0.15% increase in GDP, and 0.03% to 0.13% increase in employment by 2030, from 2014 level. This work included highly aggregated sectoral impacts that output of OWFs would increase while outputs of highly aggregated non-energy sectors benefited slightly from the higher OWF productivity. Graziano et al (2017) also used the same CGE model to assess the macroeconomic impact of increased capacity of 52 GW by 2030. The results showed that the peak installation reached in 2024 when GDP increased 0.43% and employment increased 0.3% from base year value. As for Scotland, CGE models have not been applied to OWFs but have been used to assess the impacts of other marine renewable energies. Allan et al (2008) examined the economic impact that the installation of 3 GW of marine wave energy capacity would have on Scotland, using a dynamic CGE model for Scotland (AMOSENVI). They found that GDP increase could reach its maximum value of £420 million in 2020 when the capacity installation is completed. Allan et al. (2014a) also investigated the impacts of increasing 1.6 GW of wave and tidal energy capacity in Scotland. The results showed that the GVA was expected to increases 0.2% and employment increases 0.22% compared to base year (2010) value.

Although CGE model has been applied to analyse the impacts of expanding OWFs and marine renewable energies, the above applications have limitations that still focusing on macroeconomic level and highly aggregated sectoral impacts on non-energy sectors (similar to reviewed other economic works in Section 2.1.3). None of the identified researches paid attention specifically to sectoral impacts on disaggregated seafood sectors nor to the distribution effects of household welfare, which are both important considering the nexus linkages between OWFs and seafood productions. Despite there is the gap in assessing the nexus linkages between OWFs and seafood productions, CGE models have been applied to independently assess the detailed sectoral impacts on seafood sectors.

2.2.3. Application to fishery

Although many fixed-price economic models such as input-output (IO) model or social accounting matrix (SAM) have been used to analyse regional economic impacts of fisheries, there are few CGE applications to fishery issues found in the literature. The main reason is that CGE models tend to be more aggregated than IO models and fishery is a small sector in the economy (Seung and Waters, 2006). In one example of a static CGE model developed specifically for fishery policy, exogenous shocks to Alaska fisheries under different closure rules were examined (Seung and Waters, 2010; Waters and Seung, 2010). Both applications using this model demonstrated the significant impacts on regional fisheries under these scenarios across important endogenous variables including output, employment, labour income, value added, factor prices and commodity prices as well as changes in household welfare. A dynamic CGE model was developed to examine fishery subsidy issues for the small island economy of the Azores (Carvalho et al., 2011). The model was run under four subsidy reduction scenarios, focusing on how the fishery sectors output, GDP, employment, household welfare responded to the subsidy reduction. These studies demonstrated that a CGE model could be used to provide deeper insights into the underlying economic mechanisms related to fishery issues, especially distributional effects on households. However, regional fishery CGE models work in an isolated manner and do not allow the dynamic flow of feedback from the ecological system to the macroeconomic system. To allow the two-way interrelationship between the ecologic side and economic side as well as the feedbacks between them, it is necessary to integrate the environment with the economy in the CGE model structure.

2.2.4. Integrated economic and ecological framework

CGE models can be used as an integrated framework linking the economy with the environment as the environment can be introduced as external functions in the model equations (Wing, 2011). Such integrated framework could investigate the relevant interactions between economic sectors and the ecosystem. Although a large literature introduces environmental issues into the CGE framework (e.g. Bergman, 2005; Wing, 2011), including environmental tax (e.g. Ciaschini et al., 2012; Scrimgeour et al., 2005), on carbon emission (e.g. Guo et al., 2014; Wing, 2006), and on climate change (e.g.

Bosello et al., 2011; Ciscar et al., 2011); however, there are limited versions of an economic-ecological CGE model regarding fisheries and OWFs.

One approach to developing an integrated framework has been to consider fish as an ecosystem service directly used as a production input. Floros and Failler (2004) built a regional CGE model linking an ecological fishery model component representing biological processes of fisheries productivity with a CGE model representing behaviour of economic agents. This model is the first regional fishery model that distinguishes between different species and identifies fisheries by region, and further integrated an economy model with two different biological production functions (Floros and Failler, 2004). Pan et al. (2007) expanded the model to represent the fishery system in detail with four fishery sectors, and used simple surplus growth models for the ecological system. Furthermore, the four fishery sectors are harvested (fishermen distinguished by gear type), aquaculture, fish processing and fish market sectors, which is more suitable to distinguish impacts across different seafood sectors. In this model, the economic and biological components are developed independently and dynamically linked externally to capture the endogenous interactions between economic and ecological systems.

Finnoff and Tschirhart (2008) developed an innovative modelling framework to combine the ecosystem approach with a CGE model to investigate the welfare changes related to regulating commercial fishing and to managing ecotourism. They focused on the impacts of different fish population recovery measures (via alternative pollock quotas) on the ecosystem and the economy, by solving both models consecutively so that the results from one model serve as input to the other model. Jin et al (2012) developed a regional static CGE model for New England to analyse effects associated with different ecosystem states on fish biomass and on fishery production output and price. Specifically, this model showed how a CGE model that is capable of yielding estimates of social welfare changes can be connected to provide information for better fishery management. All these examples of integrated CGE models provide the view of economic changes in response to shocks to the natural environment, but they still stay at ecosystem services level.

Recently, the integration of environmental components into the CGE framework has been extended to incorporate both natural capital and ecosystem services. A review by Banerjee et al (2016a) concluded the feasibility of integrating environment to economy, and showed three examples to illustrate how to link natural capital with CGE model. Although fish is mentioned as one example, only method was mentioned and no practical application was provided. There are limited existing works integrated other types of natural capital with CGE model. Ochuodho and Alavalapati (2016) provided a methodological framework to integrate timber as natural capital into national economic accounts and further integrated it into a static CGE model, which works as an effective tool for timber resource management and policy analysis. Comerford (2017) discussed data availability for natural capital and ecosystem services, and structural adjustment in dynamic CGE model. This work gave methodological functions to integrate natural capital from production side (ecosystem services use as production inputs, e.g. agricultural biomass, fish) and consumption side (ecosystem services use as final demands, e.g. recreation). Further this framework was applied to the agriculture sector so that agricultural biomass ecosystem service flows were used as an input into agricultural production (Allan et al., 2018). Such a framework provides the feasibility of tracking how natural capital stock interacts with economic activity, and how economic change impacts on natural capital, providing the two-way interrelationship between economy and environment. However, an approach of this kind could be use as reference to fishery as well but has not been applied to fisheries yet.

In conclusion, only a few works have focused on the marine renewables, mainly because marine renewables have rapid development in recent years. These works place more emphasis on impacts on macro-economy (e.g. GDP and employment) whereas they lack sectoral impacts on seafood productions which they have nexus linkages and lack distributional effects across households. There are limited number of CGE model applications to fishery policies as fishing sector is a small sector in economy. However, these model results show that impacts on fishing sector as a small sector could be significant and there are potential distributional effects across households. These works show that CGE model is capable of assessing the macroeconomic and sectoral impacts, as well as impacts on households. As for energy-food nexus, the most CGE model applications focus on nexus between biofuels and agriculture have not been applied on nexus linkage in marine environment before. Even fewer studies have tried to integrate both natural capital and ecosystem service to a CGE model to extend the scope of the model. Therefore, a gap in CGE model application has been identified that a CGE model is needed to be able to provide quantitative macroeconomic assessment on both OWFs and seafood productions, on their nexus linkages, on distributional effects across different households, and on the macro-economy, from economic and environmental perspectives.

2.2.5. Comparison between static and dynamic CGE model

As reviewed above, CGE models are a standard tool for empirical analysis; are widely used in nexus assessment, including for marine renewables and fisheries; and attempt to incorporate natural capital and ecosystem services. Both static and dynamic CGE models share the same model structure that is formulated as a set of simultaneous linear and non-linear equations defining the behaviour of economic agents and the economic conditions making the model reach equilibrium (Thurlow, 2004). In general, static CGE models concentrate on the comparison before and after a policy shock under equilibrium conditions while dynamic CGE models address the adjustment path between the two equilibrium conditions (Babatunde et al., 2017; Pratt, 2009; Thurlow, 2004). It should be noted that neither static nor dynamic CGE models are forecasting models but rather simulation models. The objective of CGE models is not being able to forecast the future but to focus on the impacts of particular policies/shocks.

The static CGE model concentrates on the comparison between the before (benchmark) and after (counterfactual) equilibrium of the economy after certain shock applied. Usually the notion of a counterfactual is used to consider *ex post* evaluation. Static CGE models are normally used to evaluate the actual performance of all economic agents in an economy after a policy/shock has occurred (Bergman, 1982; Britz and Roson, 2018). The static effects mainly relate to the reallocation of resources and expenditures in response to changing relative prices, which provide information on the policy-induced changes of economic variables such as GDP, production, consumption, prices, etc. The interpretation of static CGE model is illustrated by Figure 2.1, which graphs the value of economic variables (in this case GDP), against time. The initial state (benchmark) of GDP is at point A. With certain policy shock (e.g., 10% increase in biofuel consumption in EU as assumed in Banse et al., 2008 mentioned above), the GDP would reach new equilibrium state at point C. A static CGE model aims to assess the comparative difference between A and C where the impact of the exogenous shock under consideration is BC while the net impact of the exogenous change on the economy are AB. The result is therefore reported as the percentage change in GDP, and other variables are reported in the same manner. In other words, the static CGE model is actually a comparative static model, shown from the change from A to C (Babatunde et al., 2017).

Another advantage of the comparative static models is that they are able to provide detailed sectoral assessment because they pay extra attention to sector disaggregation, as demonstrated by the literature cited in the previous review, which all concentrated on highly disaggregated small sectors (e.g. fishery sectors in Jin et al., 2012; Seung and Waters, 2006; Waters and Seung, 2010; and forestry sectors in Ochuodho and Alavalapati, 2016 as reviewed above). However, the main disadvantages of the static CGE models are that the time T for the economy to adjust to the new CGE equilibrium is not given, and the adjustment path is ignored (dashed line between A and C) (Babatunde et al., 2017; Pratt, 2009).

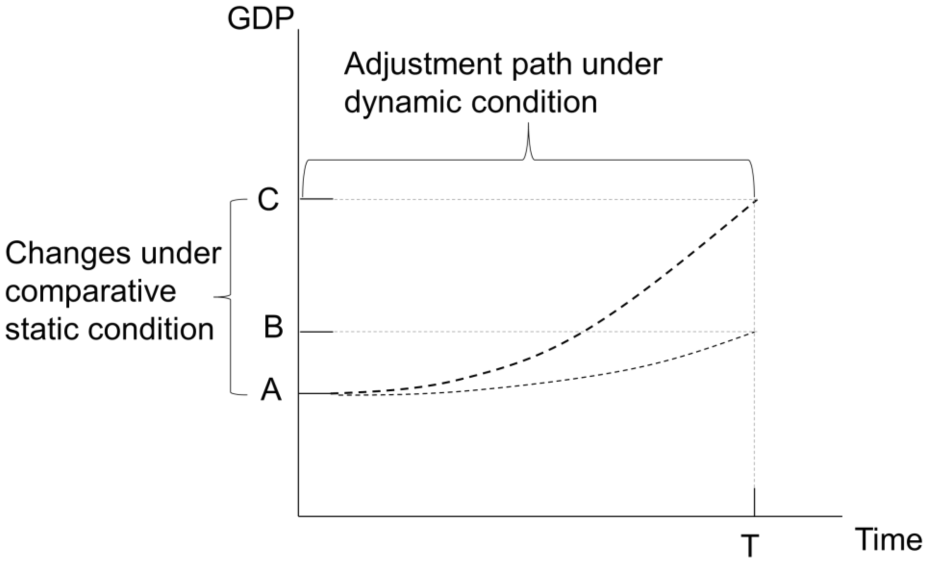

Figure 2.1 Static and dynamic CGE model interpretation (Adapted from Babatunde et al., 2017)

Dynamic CGE models are essentially comparative static models but are capable of tracking the adjustment path between initial and post-equilibrium conditions over time T (dashed line in Figure 2.1). The dynamic dimension is incorporated in the model in two ways. The first one is the recursive dynamic which is achieved through a series of exogenous shocks (e.g., labour supply curve, investment occurs under depreciation and sectoral desired capital) applied over a given time frame (e.g., Allan et al., 2014;

Arndt et al., 2012; Carvalho et al., 2011; Kretschmer et al., 2009; Timilsina et al., 2012 as reviewed above). In fact, recursive dynamic is the dynamic ordering of static equilibria. The second one is the forward-looking dynamic, which allows more specific assumptions on economic decisions (e.g., investment decision under intertemporal optimisation condition) in period *t* to affect parameters in consecutive periods (e.g. Allan et al., 2014, 2008; Graziano et al., 2017; Lecca et al., 2017 as mentioned above). Compared to the static models, the main advantage of the dynamic models is that they are better at considering how the economy might adjust to the shock at equilibrium state over time (dashed line in Figure 2.1), with results produced for each year of the simulation. Correspondingly, the disadvantage of the dynamic CGE model is their complexity, with more data required (e.g., the depreciation rate, the steady state growth rate, etc.) and assumptions needed (e.g. exogenous labour supply curve). Therefore, compared to static models, less consideration would have been placed on dynamic models' regional and sectoral details as the level of detail in the data is difficult to achieve (Babatunde et al., 2017).

To find out if the choice of CGE model would have significant impact on the simulation results, one study compared the impacts of same economic shock on the model results from static, to recursive dynamic, and finally to forward-looking dynamic CGE models (Pratt, 2009). The main conclusion from this study shows that results are of the same direction and similar magnitude across three phases of the CGE model. In particular, as capital is endogenous in dynamic models, there are relatively more significant impacts on capital and investment than is the case in a static model (Pratt, 2009). Such results highlight the fact that the choice on the type of CGE model would not necessarily overturn the model results. Under this circumstance, the contributions of static and dynamic CGE models are similar on demonstrating the direction and the magnitude of policy shock on an economy.

After comparing the above static models with dynamic models, it was decided that the static CGE model is the appropriate nexus assessment tool for this thesis for three reasons. First, the research objective of this thesis is assessing the nexus linkage between OWFs and seafood sectors, for which a static model is preferred because it can isolate the effects of individual economic shocks and fix the irrelevant economic development. Compared to dynamic models, static models reduce the number of assumptions to be made, uncertainties and possible inconsistency problems (Bachner et al., 2019). It is important to note that static model is not a forecasting model, but rather a simulation model to highlight the direction and relative magnitude of adjustments to the economy. Its stripped down character, and in particular its static nature and fixed aggregate factor supplies, are designed to focus on the key aspects of the nexus interactions which are the main concerns of this thesis. These are the impacts on the distribution of resources across sectors and incomes across households. Second, extra attention should be paid to disaggregated OWFs and seafood sectors as they tend not to be isolated sectors in SAMs: OWFs are a newly developed technology and seafood sectors are small in the overall economy. A static model allows disaggregation of specific sectors with nexus linkages. Such disaggregation is hampered by the complexity of dynamic models. Lastly, a static model is the appropriate choice under the time and resource constraints of building a model from zero. It is necessary to build the model from scratch, for the specific context of energy-food nexus between the rapid developing OWFs and commercially and traditionally important seafood production. Model construction required structural development to cover all three dimension in the nexus, to determine the appropriate functions and parameters used in the model, and finally to transform all into coding and computing. All the building processes will be presented in next chapter.

2.3. Conclusion

Given the economic and environmental importance of offshore wind power generation together with the economic and cultural importance of marine fisheries, understanding the implications of OWF development paths is important for stakeholders seeking mutually beneficial solutions that minimize conflict and maximise the synergies between OWFs and fisheries. As reviewed above, there are many qualitative assessments of the environmental linkages regarding the nexus linkages between OWFs and fishing activities. Furthermore, introducing the ecosystem services and natural capital approach could support more detailed evaluation of nexus impacts and extending the impacts from environmental dimension to covering social and economic dimension as well. Therefore, a macroeconomic assessment is necessary to quantify the trade-offs between OWFs and seafood production from the energy-food nexus perspective, covering environment, economy and social dimension. This fits back to the second and empirical objective of this thesis is to identify and assess the economic and environmental linkages between offshore wind energy and seafood production, which can help maximize synergies and minimize trade-offs within the energy-food nexus.

This thesis chooses CGE model as the macroeconomic assessment tool. There is a gap in CGE model application that no CGE model has been built with particular concern over the nexus linkages for OWFs and seafood. Therefore, this thesis aims to develop a CGE model called Scottish Economy Marine Model (SEMM), which explicitly isolated offshore wind and seafood production sectors to highlight their nexus linkages. The basic CGE model structure only covers the socioeconomic impact so that two additional modules are developed to include environmental impacts. One innovative marine resource allocation module is created to represent the replacement of fishing grounds by OWFs from fishing activities. Another module tries to develop a framework of integrating natural capital and ecosystem services with the CGE model to build the bridge allowing the feedback between economy and fish stock as natural capital. The next chapter presents the description of SEMM model and these two additional modules.

Table 2.2 Summary of the main CGE model application literatures reviewed in Section 2.2

Paper	Model	Model description	Region	Shocks	Results
Allan et al., 2008	Forward-looking dynamic regional CGE model	− 25 industry sectors: especially 5 energy commodities − 1 household − 1 government − 2 foreign sectors: rest of the UK (RUK) and rest of the world (ROW).	Scotland	Installation of 3 GW of wave energy	This paper examined the economic and environmental impacts on Scotland of the installation and operation and maintenance of 3GW capacity of wave energy. The results showed that marine renewables could not only be beneficial in reducing GHG emission, but also positively affected the Scottish economy in terms of GDP, employment and population.
Allan et al., 2014	Forward-looking dynamic regional CGE model	Same as Allan et al. (2008)	Scotland	Increased in wave and tidal energy capacity (1.6 GW): introduced as increased export	This paper explored the macroeconomic impact of increased marine energy capacity using two economic models. I-O model results showed that GVA increased 0.6% and employment increases 0.5%, whereas the CGE model results indicated that GVA increased 0.2% and employment increases 0.22% compared to base year value (2010). By comparing two models, it could be concluded that the choice of model has significant impacts on the results since I-O modelling approach tended to overestimates the results.

Arndt et al., 2012	Recursive dynamic regional CGE model	– 58 production sectors: especially 26 agriculture sectors – 15 households: by per capita expenditure – 1 government – 1 foreign sector	Tanzania	6 biofuel scenarios: 1. small scale of sugar production with land 2. large scale of sugar production with land 3. small scale of sugar production without land 4. small scale of cassava production with land 5. small scale of cassava production without land 6. a mixed production	This paper evaluated the possible trade-offs between biofuel and food production in low income country. The results indicated that the expansion of biofuel would bring positive impacts on economy by increasing national GDP and new employment. Land allocation from agriculture to biofuel did exist among individual farms, but such trade-off was not significant at national level. Household may gain welfare by growing small scale biofuel.
Banse et al., 2008	Global static CGE model	– 23 production sectors: distinguishing agricultural sectors for biofuels – 1 household each region – 1 government each region – Foreign sectors: 37 regions	Global	10% biofuel target in EU	This paper assesses the impact of EU biofuel target on agriculture market. The results reported increases in world price of oilseed, cereal and sugar by 8.5%, 6% and 2%, respectively. It showed that increased demand for biofuel had negative impact on agriculture. The land use would shift to biofuel production and eventually decrease the biodiversity.

Carvalho et al., 2011	Recursive dynamic multi-region CGE model (AzorMod)	– 45 production sectors: produce 45 commodities – 6 households: by income level – 2 government: regional and central government – 4 foreign sectors: mainland Portugal, European Union, United States of American (US), Rest of the World (RoW)	Azores, Portugal	4 fishery subsidy scenarios: 1. total elimination of all subsidies to the fish harvesting sector; 2. 12% annual reduction of all subsidies to the harvesting sector 3. elimination of all subsidies to fish processing sector 4. 50% increase in all subsidies to fishing sector	This study analysed the social and economic impacts of fisheries subsidy policies beyond the fishing sector and into the larger economy. The results suggested that reduction in fisheries subsidies would have substantial effects on the economy at the regional level, but effects were largely confined to fishing sectors. On the contrary, increase in fisheries subsidies would benefit the fishing sector but negatively affected the rest of economy.
Floros and Failler, 2004	Static regional CGE model Surplus growth models: Pella-Tomlinson and Fox models	– 29 production sectors: produce 37 commodities – 2 households: fisheries and non-fisheries – 1 government: 6 taxes – 1 foreign sector: Rest of the World (RoW)	Salerno, Italy	2 scenarios: 1. Foreign fleets exactly follow the variation in effort allocation of the Italian fleet 2. Foreign fleets do not modify their fishing effort.	This paper was one of the first attempts to apply CGE model for fisheries, with distinguishing fish species and regions. The main aim was developing a framework to provide the link between biology and economy using CGE model. Two different scenarios of reactivity were tested in the model to illustrate the potential range of responses of the stock to fishing exploitation, but no economic simulations were discussed.

Finnoff and Tschirhart, 2008	Recursive dynamic regional CGE model Ecosystem model (simple surplus growth models)	− 3 production sectors: fishery, recreation and tourism, and composite sector − 1 household − 1 foreign sector	Alaska, US	1 fishery management scenarios: reduced 30% pollock quota	The paper linked CGE model with an ecology GEEM model, covering 8 species consisting of a full food web. Reduction in fish quota of pollock brought benefit across the ecosystems that helped Steller sea lion recovery and further the entire tourism. Fishing sector reduced output with substantially increased regional fish price. The other two sectors positively affected through the reallocation of production factors.
Graziano et al., 2017	Forward-looking dynamic regional CGE model (UKENVI)	− 25 production sectors: 1 electricity transmission and 8 of electricity generations − 1 household sectors − 1 government − 2 external sectors: rest of European Union and rest of world.	UK	3 increased offshore wind capacity to 52 GW scenarios: 1. Baseline scenario with limited local content 2. UK content reached same level as onshore wind 3. Decreasing government support	This paper quantified the macroeconomic impacts of expanding OWFs under three different local content scenarios. The model results showed that the peak installation reached in 2024, GDP increase 0.43% employment increase 0.3% from base year value. The shock terminates in 2030 while GDP and employment still higher than base year value. Changes in GDP were higher than in employment meaning that the capital stock is increasing more than labour in all periods. Considering the whole economy, the cost of capital falls, while wages are increasing, thus generating demand for capital services.

Jin et al., 2012	Static regional CGE model Marine food web model	– 5 production sectors: commercial fishing, seafood processing, agriculture, manufacturing, and all other sectors – 9 households: by income level – 1 government – 1 foreign sector	New England, US	3 different ecosystem states: 1. 200% increase in piscivores production; 2. Elimination of carnivorous zooplankton; 3. Increased production of the benthos	This paper linked CGE model with marine food web model to estimate the economic effects of changes in alternative fishing practices. The model results demonstrated that changes in fishing practices in three scenarios positively affecting the economic and ecosystem. Increase in fish biomass led to increase in fishery output, further increased total seafood supply, exports, and declines in imports and prices through the economic reactions within the CGE model. One interesting finding was that the economic benefits were not evenly distributed across households, illustrating their different consumption behaviour.
Lecca et al., 2017	Forward-looking dynamic regional CGE model (UKENVI)	– 25 production sectors: 9 electricity generation sectors – 1 household – 1 government – 2 foreign sector: rest of European Union and rest of world.	UK	1 energy scenario: 30% reduction in levelized cost of offshore wind energy by 2030 from 2014 level	This paper focused on the economic and environmental impact of reductions in the cost of offshore wind using a CGE model. The productivity shock in the offshore wind sector generated a substantial impact on the whole economy - GDP increases by 0.03% and 0.15% in short (first period) and long-run (50 periods), despite the sector accounts for only 0.026% to UK economy. The employment increase 0.13% in the long run. Total CO2 emission fall by 25 Mt which indicates to be sensitive to the elasticities of substitution amongst generation technologies.

Pan et al., 2007	Forward-looking dynamic regional CGE model Biology model (Surplus growth model)	– 5 production sectors: further disaggregation of fishery sector – 9 households: by income source – 1 government – 1 foreign sector	Salerno, Italy	2 fishery policies: 1. Species protection: 20% tax on consumption of some fish species; 2. 10% tax on all the species	This paper attempted to link the economic and ecological system in a CGE model, with particular focus on fisheries. The results roughly showed that applying tax on some fish assumption can protects these fish species while harm other fish species, which highlighted the potential trade-offs between species when considering policies to protect certain species. Conversely, applying tax on all fish species, the biomass stock of all the species would increase from the baseline but the household consumption of aquatic product will decrease.
Seung and Waters, 2010	Static regional CGE model	– 18 production sectors: produce17 commodities (specifically including 2 fish harvesting and 2 processing sectors) – 9 households: by income level – 1 foreign sector: rest of world (ROW) – Two closure rules: **Neoclassical:** no movement of factors: **Keynesian:** flexible labour	Alaska, US	3 Alaska fisheries scenarios: 1. 10% reduction in Alaska pollock TAC; 2. 50% increase in fuel price; 3. 3% reduction in the export price for seafood	This paper tested different fishery policies from both supply side and demand side using CGE model. The model results reported macroeconomic variables. Generally, reduced TAC had negative impacts on fishery sectors whereas non-seafood sectors slightly negatively affected. The impacts of higher fuel price are larger on average in percentage terms for seafood industries than for aggregated non-seafood industries as seafood production was fuel-intensive. Welfare loss is greatest for high income households under all experiments. The impacts estimated in Keynesian closure variant are larger than neoclassical closure.

Ringler et al., 2016	Global recursive dynamic CGE model (IMPACT)	– 62 production sectors: distinguishing 39 crops – 1 household each region – 1 government each region – Foreign sectors: 159 countries	Global	4 scenarios: 1. business as usual 2. additional fossil fuel tax 3. increased biofuel use 4. low fossil fuel price	This paper described the complex relationship between energy price changes and food and water security with one particular scenario concerning biofuel expansion. The biofuel scenario results showed global staple price increased and ripple-on impacts on processed food in response to increased use of biofuel in energy production. Global food price would increase directly in the feedstock commodities and indirectly in other agriculture commodities due to the competitiveness on land and thus increased land rents.
Timilsina et al., 2012	Global recursive dynamic CGE model (IMPACT)	Same as Ringler et al. (2016)	Global	2 biofuel scenarios: 1. announced targets of biofuel usage by countries; 2. doubling the announced targets	This paper analysed the impacts of global expansion of biofuels on agriculture and food supply. The results showed that Expansion of biofuel wouldn't have large impact on global food supply, but there would be significant regional impacts. The main biofuel feedstock (e.g. sugar, corn, oilseeds) price would increase by 1% to 9% in 2020. Global forest would loss significantly to give land to reach biofuel targets.

Waters and Seung, 2010	Static regional CGE model	Same as Seung and Waters (2010)	Alaska, US	3 Alaska fisheries scenarios: 1. a 31% reduction in the walleye pollock allowable catch; 2. a 125% increase in fuel price; 3. both shocks simultaneously.	This paper used CGE model to estimate regional economic impacts of a fishery management. Impacts of higher fuel prices tend to be relatively large in percentage terms for seafood sectors compared with most non-seafood industries Income and welfare loss was greater for higher income households under both experiments due to their relatively greater participation in factor markets. The combined impacts in scenario 3 were nearly additive the first two results.

3. Methodology

The energy-food nexus is a holistic concept to identify trade-offs and synergies between energy and food, and thus better understand complex interactions between multiple natural resource systems. By maximizing synergies and minimizing trade-offs, the nexus approach further aims to internalize social and environmental impacts and guide development of cross-sectoral policies (Kurian, 2017). Although the nexus approach provides the concept of integrated resource management, development of an appropriate quantitative framework is necessary to evaluate the interlinkages between nexus elements (Bazilian et al., 2011). Furthermore, an integrated environmental-economic modelling framework could comprehensively better inform effective policy and regulatory design by identifying the impacts of each nexus element on the other nexus elements covering both socio-economic structures and state of the environment (McGrane et al., 2018).

In this thesis, the static computable general equilibrium (CGE) modelling approach is chosen as it enables the assessments of nexus linkages and helps to identify trade-offs and synergies at both macroeconomic and sectoral levels of the economy. The CGE model results are capable of providing indications to food and energy security, mainly regarding their availability and affordability. The availability is measured through the sectoral outputs. Compared to fixed-price economic models, a key advantage of CGE models is the endogenous determination of price variations, which shows the changes in affordability. When considering the nexus in an economic framework, the interconnections among nexus elements are mainly caused by competition for limited productive resources resulting from production and consumption linkages. Such linkages will affect all agents and markets within an economy through the circular flow of income and spending so that a CGE model is capable of capturing the impacts on the whole economy.

This chapter outlines a static CGE model built specifically for this thesis, embodying increasing levels of sophistication as the research progresses. It is divided into two sections. The first section describes the general structure of a standard CGE model, starting with the circular flow of income and spending in an economy, followed by the essential components of general CGE models. The second section describes the model built specifically for this thesis, called Scottish Economy Marine Model (SEMM), including the basic structure of the SEMM, the development of two novel, advanced frameworks which include introducing a marine resource allocation module and integrating natural capital in the basic SEMM structure.

3.1. General CGE model structure

3.1.1. General equilibrium theory

3.1.1.1. The circular flow in the economy

A CGE model is a large-scale economy-wide numerical model that simulates the core economic interactions in the economy. It describes the behaviour of all basic economic elements in an economy and the linkage among them through the circular flow of income and spending, which defines the structure of an economy.

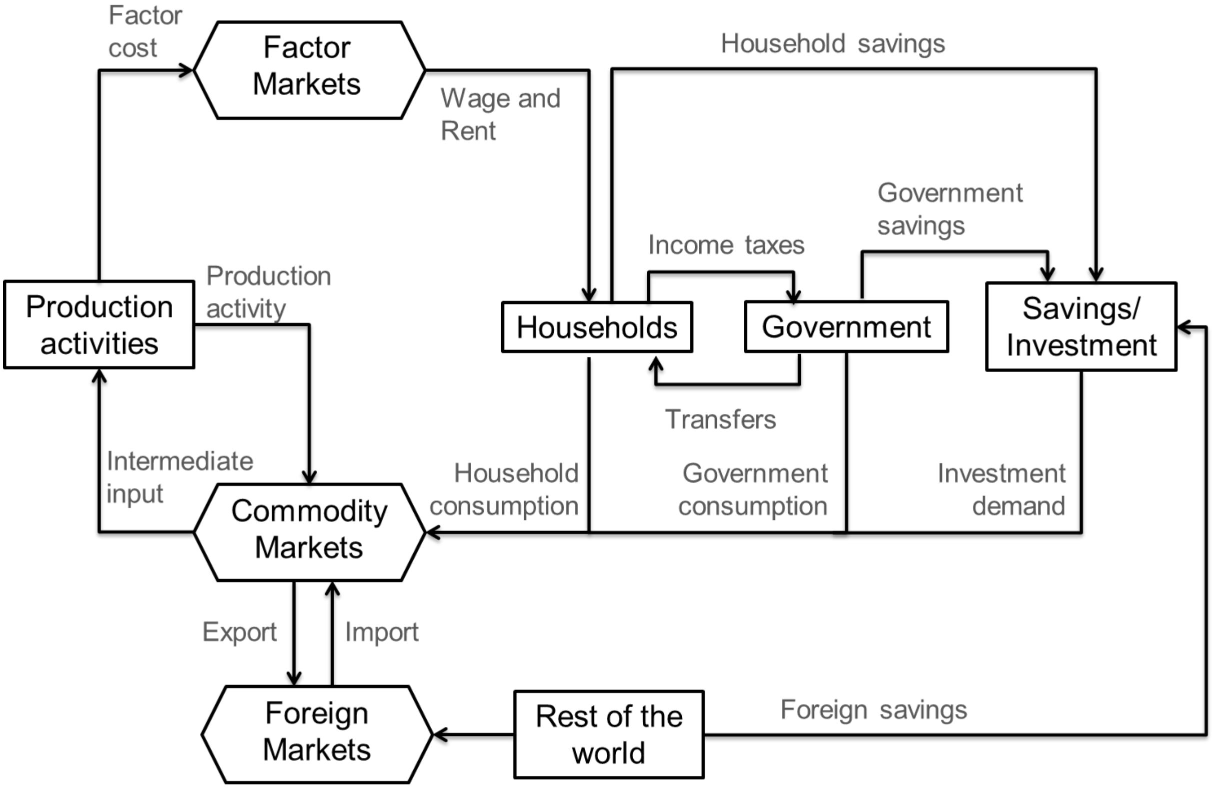

Figure 3.1 Circular flow of income and spending in CGE model, with economic agents represented by rectangles and markets by hexagon (Adapted from Breisinger et al., 2009)

Figure 3.1 depicts the circular flow of income and spending in an open economy between a set of elements which include: production activities (inter-industry intermediate consumption), commodities markets, factors markets (labour, capital), institutions (households, government), economic accounts (savings-investment account, Rest of the World account). The economic commands in a CGE model include behavioural equations which capture production and consumption decisions for economic agents (shown as rectangles in Figure 3.1), system constraints to define equilibrium in factors and commodities markets, and macroeconomic balances for savings-investment, government and current account of the Rest of the World (Löfgren et al., 2002).

Production activities use labour and capital as well as other intermediate inputs to produce commodities consumed by institutions, leading to production linkages between producers and consumers. Labour and capital are owned by households and government who receive their income from labour wage and capital rent and in turn buy goods and services, leading to the consumption linkage. The flow of commodities constitutes the commodity markets while the flow of labour and capital makes up the factor market. Mediated through commodity and factor markets, the economy reaches a balance between demand and supply by adjusting prices. As an open economy, commodities can be exported and imported with the rest of the world through the foreign market. The government collects direct and indirect taxes from other domestic economic agents as revenues while buying commodities and making transfer payments to them as subsidies and welfare. The last account is investment-savings which records savings of institutions and demand for capital goods. Considering the linkages originating from all economic agents in this circular flow chart, any change in decisions made by one economic agent will inevitably affect the rest of the economy since all agents and markets are interlinked. This specific feature makes the CGE model a powerful tool for nexus assessment. Key variables and parameters can be determined exogenously. The subsequent impact of changes in one nexus element on other nexus elements through both direct linkages between sectors and indirect linkages in the overall economy can be captured.

All agents are linked through production and consumption linkages. Production linkages may emerge from intermediate input linkages. For example, electricity is an essential intermediate input for all productions and fish is a crucial input in fish processing. Therefore, increasing the price of one commodity would inevitably change costs in other production sectors. Besides, potential trade-offs between factors of production may arise, especially when they involve scarce natural resources, e.g., land competition for expanding biofuels and agriculture. The consumption linkages become apparent through changes in commodity sales and prices, which change the corresponding demand and thus trigger change in production as the supply expands to meet the new demand to reach an equilibrium. Food and energy production is connected through such economic linkages from the nexus perspective.

3.1.1.2. General equilibrium theory

A CGE model encompasses the above circular flow of income and spending following the economic theory of Walrasian general equilibrium theory. Under the equilibrium theory, economic agents find their optimal solutions under a set of constraints, with producers maximizing their profits subject to technology constraint while consumers maximize their utility subject to budget constraint. The optimization problems are solved against three equilibrium conditions:

a. Market clearance: a given level of output produced by production activities must be completely consumed by consumers by intermediate and final demands. Analogously, for a given factor, the demand from production activities must match with the supply endowed by institutions. In factor and commodities markets, price adjusts until demand for each commodity/factor is equal to its supply.
b. Zero profit: for the production activities, the total revenue collected from their production must be allocated either to households, to the government, or to the other economic agents. Producers maximise their profits and sell their commodities in perfect competitive markets where individual producers cannot influence the market prices of outputs or inputs (Burfisher, 2017). That maximum profit simultaneously equals zero profit reflects the fact that production is assumed to operate under constant returns to scale implying that average costs equal marginal costs (Roson, 2006).
c. Income balance: the consumers' income should be exhausted on commodity purchases and savings. The sectoral composition of household consumption is determined using the assumption that consumers maximise utility and spend all the income they receive (minus savings) from supplying labour and capital to productions.

The three equilibrium conditions ensure that under optimal conditions, the solution values for all endogenous variables must be nonnegative[3] (Springer, 1998). They also ensure the model solves the non-linear equations satisfying the necessary first order necessary conditions (Springer, 1998). In other words, the allocation of resources and commodities among economic agents is solved by simultaneous equations for a set of prices, quantities and income levels under these three conditions (Wing, 2004). It refers to the model is run under neoclassic theory which does not include the existence of imperfect competition and monopoly-pricing (Thurlow, 2004). The adjustment of market prices and quantities brings the economy to equilibrium after specific exogenous shocks and it balances resource allocation in the economy (Burfisher, 2017), these features make CGE modelling suitable for economic analysis of the nexus.

It should be noted that the price changes here refer to relative prices (defined as relative to a numeraire) as the model assumes no interactions between monetary system and the model economy. The money neutrality assumption is criticized in that nominal change would have impact on the real economy, in particular within the short-run and in respect to the demand for money balances (Taylor, 1983). However, the CGE model concentrates more on the medium- and long-term resource allocation, which avoids the possible influence from the money neutrality assumption (Dervis et al., 1982). Furthermore, given the associated costs in the form of data, complexity and additional research time, it is still unclear in what context the benefits from including money neutrality would be significant (Robinson and Löfgren, 2005). The use of a numeraire and the lack of an explicitly modelled monetary sector imply that the model is essentially one of a barter economy in which money is neutral (Thurlow, 2004). Classic static CGE models do not incorporate the sorts of financial variables such as non-neutrality of money, inflation, expectations on investment, which involve links between the financial and real sides of the economy. Nonetheless, a CGE model provides a good framework for analysing issues of economic structural adjustment: the impact of shocks that work through changing prices and market incentives to affect resource allocation and the structures of production and consumption.

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[3] General equilibrium models can be formulated and efficiently solved as a complementarity problem in which the optimum value of each variable is characterized by complementary slackness (Mathisen, 1985). This means that producers earning negative profit will be closed with zero output so that the solutions in CGE model will be nonnegative.

Generally, a CGE model describes the economy from both macroeconomic and microeconomic perspectives. At the macroeconomic level, the basic economic agents and markets are included in the model structure following the complete circular flow of income and spending in an economy under general equilibrium theory (Figure 3.1). As for the microeconomic level, the behaviour of these economic agents is defined by a set of microeconomic functional forms. The next sub-section will explain the basic elements of a CGE model regarding the choice of different microeconomic theories.

3.1.2. Elements of a general CGE model

This section discusses about the basic elements in a normal standard CGE model, including the model structure, all the available functions, and different macroeconomic closure rules. Before building a model from zero, it is necessary to discuss all the available essential elements in a normal standard CGE model to better build a CGE model for the purpose of this thesis.

Figure 3.2 shows the basic structure of a standard CGE model where the economic agents and main markets in the circular flow of income and spending in Figure 3.1 are all included. Under the equilibrium conditions mentioned above, economic decisions made by producers and consumers in the model are the outcome of optimization problems under a set of constraints with different choices of microeconomic functions.

First, **production activities** produce commodities for sale to foreign market (i.e., export) and domestic market (i.e., households, other producers as intermediate inputs, government and investment). They in turn pay taxes to the government and employ factors of production and intermediate inputs, both domestic and imported. The producers maximise profit subject to a production technology constraint. Profit maximization implies that the factors receive income where the marginal revenue equals marginal cost based on endogenous relative prices. Production is typically modelled through a nested structure to allow more flexibility, as shown in Figure 3.2.

Next, **exports** and **imports** are determined by optimizing behaviour under certain constraints. Exports are given as a result of profit-maximizing behaviour. The CGE model assumes imperfect substitutes between foreign goods and domestic commodities to account for two-way trade of the same commodities (Armington, 1969). This means that commodities and their prices differ with regard to origin and destination. The imperfect substitutes allow the model to better reflect the empirical realities of most countries (Löfgren et al., 2002). For a single country CGE model, the small country assumption is often applied which implies that the economy faces a perfectly elastic world demand at a fixed world price

Then, **households** supply factors of production activities in return for income, consume domestic and imported commodities and make resources available for investment through savings. **Government** collects taxes from production activities and households, borrows from abroad and makes transfer payments, for example, subsidizes particular agents or activities. A static CGE model has no explicit modelling of the **investment** decision, the aggregate level of investment is derived as the sum of savings as retained earnings of households, the government net balance and the foreign inflow of capital. Normally, the disaggregation of investment is translated into demand for goods and services used to produce the investment goods.

The behaviour of economic agents mentioned above is described by economic functions that can applied in a CGE model. There are common production functional forms defining various production technologies. These include Leontief, Cobb-Douglas (CD), and Constant Elasticity of Substitution (CES) functions. Leontief functions often refer to situations where the ratio of inputs is determined by technology rather than by the decision-making production activities (Thurlow, 2004). CD and CES are more flexible and used in most CGE models to allow substitution between inputs when relative price changes. Exports are normally modelled by a constant elasticity of transformation (CET) function, making the production activities sell their commodities to markets where they can receive highest returns. The returns are based on the price difference between domestic and export price, where the latter is determined by the foreign price times the exchange rate. Imports are often determined by an Armington function which allows imperfect substitutability between domestic and foreign markets. Household consumption preferences functional forms in CGE models are often represented by a linear expenditure system (LES), Cobb-Douglas, or CES utility function. The behaviour of government is normally not constrained by optimizations so that changes can be given exogenously, which is also better for policy analysis (Robinson and Löfgren, 2005). As for investment, investment on goods is assumed as a fixed share of the total investment, implying no real compositional shift in investment when relative commodity price changes (Thurlow, 2004). The choice of functions in a CGE model is determined by the objectives of the particular research.

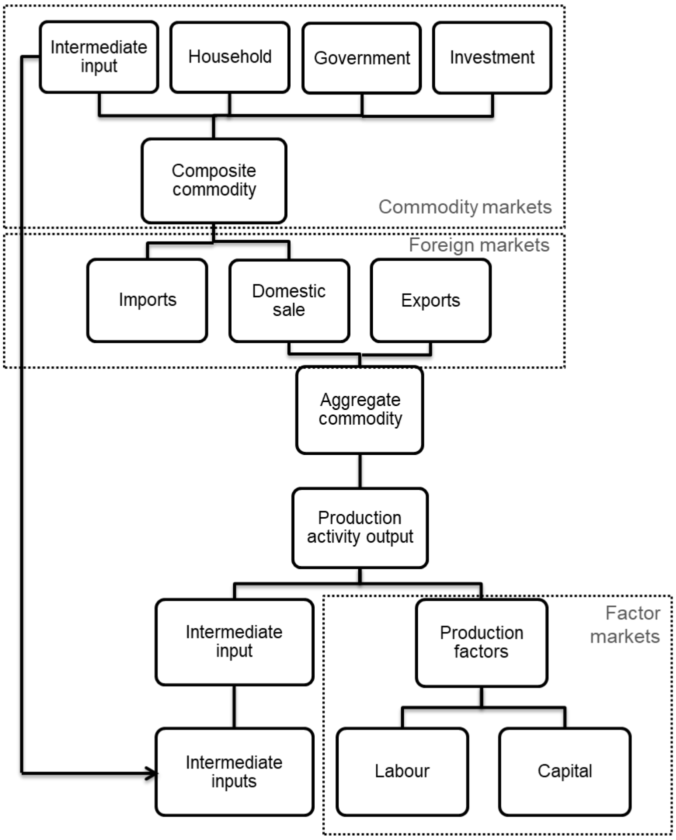

Figure 3.2 Nested structure of a standard CGE model

Finally, the circular flow is completed by equations showing macroeconomic balance between supply and demand of commodities and factors, corresponding to the market clearing requirement mentioned above. There are a number of system equations which the model must satisfy. These include both **market clearance** conditions and the choice of **macroeconomic closure** for the model.

For commodity market clearance, demand (including household and government consumption, investment spending, and exports) must equal supply (including domestic production and imports), through the adjustment of endogenous prices. The different factor market clearance conditions are briefly discussed below. The mechanism for reaching equilibrium in factor market depends on how the relationship between factor supply and wage is defined. One setting is classical full employment assumption by fixing the factor supply (exogenous) and allows an economy-wide wage to vary (endogenous) to reach the equilibrium. This assumes free mobile factors between sectors, given long enough time to re-allocate the factors. Alternatively, a Keynesian type unemployment assumption allows fixed economy-wide wage so that the factor supply is various to record the demand of production activities (Löfgren et al., 2002). Another option is that factor demand is sector-specific which is fixed at base-year quantity while the sector-specific wages are varied to reach the equilibrium. This option is preferred in short-run analyses when there is not enough time to allow factor movements (Löfgren et al., 2002).

Apart from the above market clearance conditions, different closure rules need to be applied in the model to ensure macroeconomic consistency and govern the behaviour of the overall model. There are three macroeconomic balances mainly determining the closure rules, which are government, international trade and saving-investment balances (Löfgren et al., 2002). For the government balance, options can be chosen from fixed tax rates or fixed government savings. For the international trade balance, which is expressed in foreign currency, fixed foreign exchange rate or fixed foreign savings are the alternative closure rules. Choice of these two alternative closure rules depends on which kind of government or which kind of trade policy is being analysed.

For the investment-saving balances, closures are either investment-driven or saving-driven. In the static CGE models, there are various ways of describing investment behaviour: On the one hand, the aggregate capital stock may be fixed and thus the investment is fixed accordingly (Piazolo, 1996). In this case, the closure is saving-driven, savings are determined by household income from which the investment is then determined. Increase in income leads to increase in savings and consequently increases in investment, which are equal to savings under the equilibrium condition. Therefore, the welfare gain induced by income will be partly offset by extra income being spent on investment instead of on commodities. Furthermore, since savings depend on income that in turn depends on the capital stock, savings depend (indirectly) on the stock of capital (Francois et al., 1999). On the other hand, the real return to capital may be held at the benchmark level and investment and capital stock adjust accordingly (Piazolo, 1996). In this investment-driven closure, the investment is exogenous and independent from income. Therefore, an increase in income, through an increase in consumption, leads to a full increase in welfare, which provide an advantage of choosing this closure (Hosoe et al., 2010). Since the total investment is decided by the depreciation rate multiplies capital stock, the process of capital accumulation is that the amount of investment is assumed to replace worn-out capital. In both the pre- and post-shock equilibria the capital stock is specific to the sector and doesn’t subsequently migrate between sectors. The capital stock would grow if savings and investment were larger than the rate at which capital depreciates, it is constant if savings and investment are just enough to replace depreciated capital, and it falls otherwise.

The closure rule determines what is included in the model as endogenous variables and exogenous variables. Several issues need to be considered before selecting the macro closure rules for the CGE model. First, the selected macro closure should be compatible with the objective of the analysis (Löfgren et al., 2002). Second, macro closure rules characterize the model structure and thus crucially affect simulation results and their implications (Hosoe et al., 2010). Third, the influence of the selected price numeraire on the simulation results must be taken into account. According to Walras's law, there is no need to impose the market-clearing conditions on all *n* markets. Because once the *n-1* markets clear, the last market will clear automatically. Therefore, the CGE models do not solve the model for all prices in absolute terms but only for relative prices. For example, if a price, such as the commonly chosen consumer price index (CPI) or gross domestic product deflator (PGDP), is chosen as price numeraire in the CGE model, then the other price changes after certain shocks are relative to this numeraire.

In general, a CGE model is a selection of behavioural functional forms of all economic agents that describes an economy as a whole and the interactions among them (Burfisher, 2017). CGE models can capture the macroeconomic structure of the economy (e.g. GDP) as well as the microeconomic elements in terms of the behavioural response of economic agents (e.g. sectoral impacts on production outputs and prices, commodity sales and prices, household behaviours). Furthermore, one advantage of CGE models is the measurement of household welfare. Estimations of welfare distribution would identify which household groups suffer the most after certain economic shocks. The equivalent variation (EV) is used in this thesis to measure the welfare changes in household utility by the income needed to make households as well off in the new equilibrium as they were in before the shock to the model evaluated at benchmark prices. Therefore, a CGE model is able to analyse the effects of shocks after they are applied to the initial economic equilibrium, and to calculate the new general equilibrium outcome after all the adjustments of price mechanisms in the economic system have occurred. This is a main strength of a CGE model, as it can be adapted to simulate a wide range of policies and research areas.

A CGE model can, and have, been applied to economies at local, regional, or national scale as long as the model is calibrated with empirical data for the specific economy. To reflect the specific economic structure, variables including production outputs and parameters such as elasticities must be computed with actual data. Therefore, a CGE model needs a comprehensive database to ensure the model is representative of the chosen economy.

3.1.3. The CGE model database

Data used for a CGE model can be broadly grouped into two categories. The first is the data supporting the economy in the model and is structured in a Social Accounting Matrix (SAM) table. The SAM accounts encompass all income and expenditure flows between economic agents within an economy in a specific year (Burfisher, 2017). CGE models rely on SAM tables to provide the initial values for variables and to make CGE models act as the representative economy. The second category is the behavioural parameters in the functions that describe the behaviours of the economic agents in CGE models.

3.1.3.1. Social accounting matrix

The CGE model is built on data provided by a SAM which is generated using input-output tables and supported by various other macro- and micro-level datasets. A SAM is displayed in a square matrix table where the row identifies income or receipts paid into an account and the corresponding column details the expenditure or payments made from that account. Each cell therefore shows payment from its column account to its row account. Each row total is equal to the corresponding column total so that in each account total expenditure matches total income. Most SAM tables contain different accounts for the main economic agents included in the circular flow of income and spending (Figure 3.1) in a certain year. Since one production activity is supposed to produce more than one commodity, there are separate accounts for commodities and activities (Breisinger et al., 2009). An example of SAM table is shown in Table 3.1. For computational and practical reasons, the SAM used for CGE model is normally aggregated into fewer, broader sectors to fit in with the model application. It is relatively simple to adjust the aggregation of the SAM to fit the aim of the model as long as there are available data. The production activity account normally follows the same aggregation provided by input-output tables or further disaggregation based on research aim. The household account can be divided into different types of household by income groups, different labour types, or age differentiation. Disaggregating the SAM enables the CGE models to measure distributional impacts. This specific feature makes the CGE model an appropriate tool for quantitative analysis of sectoral impacts on specific sectors and distributional policy impacts in terms of different household categories. The equations of a CGE model utilize data for an actual SAM for some base year which means that the aggregate and detailed production levels and expenditures are at the same level as the base year (Burfisher, 2017).

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Table 3.1 The basic structure of an aggregated social accounting matrix (Adapted from Löfgren et al., 2002)

	Production Activities	Commodities	Factors	Households	Corporation	Government	Investment-Savings	Rest of World	Total (Income)
Production Activities		Domestic supply							Activity income
Commodities	Intermediate Inputs			Households Consumption (C)		Government Consumption (G)	Investment demand (I)	Exports (E)	Demand
Factors	Value-added								Factor income
Household			Factor income		Transfers to household	Transfers		Transfers	Household income
Corporation			Capital 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 (M)			Transfers towards RoW	Transfers			Foreign exchange inflow
Total (Expenditures)	Activity expenditures	Supply	Factor expenditure	Household expenditures	Corporation expenditures	Government expenditures	Investment	Foreign exchange inflow	

3.1.3.2. Elasticities database

In addition to the SAM as an essential database for the CGE model, it is important to choose the functional forms and parametrization of the equations that will represent the economic flows in a SAM. Once the functions have been decided based on the model's assumption, there will be various types of parameters that need to be imposed. Calibrating a CGE model requires specifying certain parameter values for the model equations. In general, there are two kinds of parameters necessary in CGE models. First, there are parameters that can be calibrated from the SAM and reveal the country-specific economic structure for the particular year of the SAM. For example, share and shift parameters in the CES functions can be calibrated from the SAM data based on the assumption that an equilibrium solution of the model is determined by the SAM base year[4]. Second, elasticity parameters need to be specified based on previous studies. Among the available functional forms for a CGE model, the CES production function, CET function, Armington function, and LES utility function need estimation of their elasticities based on survey work from published studies or available databases (Hosoe et al., 2010). The model simulation results depend on the size of the parameters specified in the behavioural functions in the model. The main elasticities need to be estimated exogenously and their ranges are listed in Table 3.2. All parameters mentioned above together with relevant equations can be found in detail in Table A1 and Table A2 in Appendix 1.

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[4] See for example of calibration procedure in Appendix 2

Table 3.2 Summery of important elasticities in CGE models

Parameters	Description	Range	Representation
σ_a^a	Elasticity of aggregate input substitution	$0 < \sigma < 1$	Complementary
σ_a^{va}	Factor substitution elasticity		
σ_c^t	Elasticity of export transformation	$\sigma > 1$	Substitution
σ_c^q	Armington substitution elasticity		
$e_{c,h}$	Income elasticity of households	$0 < e_{c,h} < 1$	Normal good
		$e_{c,h} > 1$	Luxury good
φ	Frisch parameter of households	-10	Very poor
		-4	Poor
		-2	Middle income
		-0.7	Better off
		-0.1	Rich

Table 3.3 shows examples of these important elasticities across major production activities and trade taken from CGE-based literature. Since the study area of this thesis is Scotland, the elasticities adopted in this model are based on the relevant elasticities mainly for UK and Scotland but with some other developed country data as shown in Table 3.3. In particular, the elasticities for the fishing and electricity sectors are highlighted below because of their significance to the energy-food nexus of this research.

Table 3.3 Examples of important elasticities among production sectors in developed countries

Model	Elasticity	Agriculture	Fishing	Electricity	Industries	Services	Manufacturing
Whalley, (1985)	σ_a^{va}	0.6	n.a.	1.0	[0.6, 0.9]	1.0	n.a.
Rimmer, (1990)	σ_a^{va}	0.4	n.a.	0.9	0.5	0.9	n.a.
Jornini et al. (1994) SALTER (1993)	σ_a^{va} (short-run)	0.4	0.4	0.9	0.8	0.9-1.2	[0.8, 0.9]
	σ_a^{va} (long-run)	0.8	0.8	1.8	1.6	1.8-2.4	[1.6, 1.8]
	σ_c^q (short-run)	2.2	2.1	2.1	1.9	n.a	2.1
	σ_c^q (long-run)	2.2	2.8	2.8	1.9	n.a	2.8
	σ_c^t	n.a	-5.6	-5.6	-5.4	-3.7	n.a
Hertel and van der Mensbrugghe, (2016) GTAP 9	σ_a^{va}	0.26	0.2	1.26	1.4	1.26	n.a.
	σ_c^q	n.a.	1.25	2.8	1.9	1.9	n.a.
Östblom and Berg (2006) EMEC (Sweden)	σ_a^a	0.3	0.2	0.1	[0.3, 0.7]	0.7	n.a.
	σ_a^{va}	0.5	0.3	0.3	0.8	0.8	n.a.
	σ_c^q	0.4	1.4	0.5	[0.3, 1.8]	0.6	n.a.
	σ_c^t	-1.1	-6	-1	[-6.3, -1.0]	-1.2	n.a.
Barnes et al. (2008) (UK)	σ_a^{va}	0.4					

Lecca et al. (2014) UKENVI (UK)	σ_a^a	0.3
	σ_a^{va}	0.3
	σ_c^q	2
	σ_c^t	2
Allan et al. (2014) AMOSENVI (Scotland)	σ_a^a	0.3
	σ_a^{va}	0.3
	σ_c^q	2
	σ_c^t	2

As listed above, the elasticities have various ranges in values due to variations in industries in different countries as well as the years and source data (Burfisher, 2017). An elasticity of substitution of less than one implies that the two goods are complements. This means that if the price of one good falls relative to the other, the share of expenditure on that good falls. Whilst there is an increase in the quantity consumed of the now lower priced good, its impact on expenditure is not enough to offset the reduction in price. On the other hand, if the elasticity of substitution is larger than one, the two goods are assumed to be substitutes and a decrease in the price of one good will increase its share of the total expenditure on the two goods. The elasticities from previous works presented in Table 3.3 provide some basis for estimation in new CGE modelling. Due to limited data and to clarify the analysis, the elasticity value is often taken to be constant across all sectors. Some parameters could be drawn from existing works while some are not available (e.g. elasticities for fishing) and thus have to be estimated, which leads to imposing an assumption of constant elasticity across all sectors (Dervis et al., 1982; Robinson and Löfgren, 2005; Thurlow, 2004). This need to impose such an assumption is a limitation of the model but sensitivity analysis can be conducted to test the impacts of different values of such elasticities on the results to test the robustness of the model. Further discussion on sensitivity analysis will be mentioned in Section 3.2.1.3.

3.2. An integrated modelling framework for Scotland

This section introduces the SEMM built specifically for Scotland with particular focus on the energy-food nexus. Section 3.2.1 is the basic structure of the SEMM. To capture the respective drivers and linkages between OWFs and seafood production in detail, two slightly different modelling frameworks have been further developed. The basic SEMM model only focuses on the production and consumption linkages between OWFs and seafood sectors. To get a fuller account, it is necessary to assess the direct trade-offs regarding the conflicting uses of the sea. The first improvement to the basic SEMM framework is shown in Section 3.2.2. This provides a direct link between OWFs and the fishing sector by introducing a new marine resources allocation module. However, there are also further environmental impacts of OWFs on fish stocks which are normally ignored by the economic assessment. Therefore, Section 3.2.3 improves the model structure by linking a classic fish harvest model with the basic CGE model to allow the assessment both from the economy side and from the environmental side.

3.2.1. Basic SEMM structure

SEMM is a single country CGE model for Scotland developed for this thesis. It is a static CGE model, which can be used to compare the economic situation before and after an exogenous shock but is not able to describe the adjustment path (Seung and Waters, 2010). SEMM adopts the International Food Policy Research Institutes (IFPRI) Standard CGE model framework which is built and solved using the General Algebraic Modelling System (GAMS) (Löfgren et al., 2002). The model is calibrated based around a Social Accounting Matrix (SAM) for Scotland for the year 2013[5] shown in Table 3.5 (Katris et al., 2019).

3.2.1.1. 2013 Scottish SAM

The basic 2013 Scottish SAM table is taken from Katris et al. (2019). It records the flows of incomes and expenditures through the Scottish economy. It is originally disaggregated to 30 production activities and five household quintiles measured by weekly income. In the SAM used in the SEMM model, the sectoral detail has been adjusted so that there are now eight sectors. To analysis the nexus linkage between OWFs and seafood production, three seafood sectors and two electricity sectors have been disaggregated from the original 30 aggregated sectors in the 2013 SAM.

The two electricity sectors are 'OWF electricity' and 'other electricity' and the three seafood sectors are 'fishing', 'fish processing', and 'aquaculture'. The remaining three sectors (i.e. 'agriculture', 'industry', and 'services') are highly aggregated to represent how the whole economy reacts to changes in the two sectors of particular interest (electricity and seafood). The treatments of electricity sectors and seafood production sectors are distinctive. Two production sectors for producing electricity, OWF electricity and other electricity, are disaggregated from the single electricity sector in the original SAM. Although OWF electricity capacity and generation has increased in recent years, its share in the energy mix was still quite limited (about 1%) in Scotland in 2013 (Table 1.3). To model possible impacts by OWFs, an initial assumption is made that the OWF electricity sector would contribute 10% of the general electricity supply (The OWFs in Scotland had reached a share of 7% of total electricity generation in 2019 as shown in Table 1.3). Therefore, in calibrating the model, a higher value

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[5] The datasets is published by University of Strathclyde and it can be downloaded at https://pureportal.strath.ac.uk/en/datasets/the-2013-social-accounting-matrix-for-scotland-disaggregated-by-h.

(10%) is imposed, rather than the actual generation level of 1% recorded in the SAM for year 2013. Although this is greater than the actual generation in Scotland, the assumption provides a useful reference point to identify the economy-wide subsequent impacts of developing OWFs (Arndt et al., 2012).

The relevant electricity row and column of the SAM are disaggregated into two sectors to initialise the offshore wind electricity sector based on a UK Input-Output table disaggregation by electricity production sectors (Allan et al., 2019). The three seafood production sectors, fishing, fish processing and aquaculture, are disaggregated based on the same year (2013) Input-output (I-O) data of Scotland.

Table 3.4 Comparison of Type 1 multiplier from 8-sector SAM in SEMM, 98-sector Scottish IO and 26-sector UK IO

	8×8 Aggregated SAM in SEMM	2013 98-sector Scottish IO (Scottish Government, 2020b)	2010 26-sector UK IO (Allan et al., 2019)
Agriculture	1.413		
Fishing	1.435	1.596	
Fish processing	1.640	1.542	
Aquaculture	1.595	1.741	
OWF electricity	2.090	1.671	2.298
Other electricity	1.588		
Industry	1.415		
Service	1.298		

Given that the aim of this thesis is to assess the nexus linkage between OWFs and seafood production, the remaining sectors are highly aggregated to simplify the modelling process and the interpretation of results without generating significant bias. To test whether the aggregation leads to significant bias on seafood and electricity sectors, the Type 1 IO multipliers is calculated for the 8×8 Leontief inverse matrix embedded in the SAM and these values are shown in Table 3.4. For the seafood sectors, these multiplier values are compared to the corresponding figures from the fully disaggregated 2013 Scottish IO table. For the electricity sectors the comparison is with the OWF sector in the electricity-disaggregated 2010 UK IO table and the aggregated electricity sector in the 2013 Scottish table.

The multiplier values give an indication of the strength of the local linkages captured in the data. The results show that there are no marked or systematic variations in the multipliers for the seafood and electricity sectors between the aggregated and disaggregated multipliers. This suggests that aggregating the remaining sectors does not result in huge bias on results of how the impacts of expanding OWFs distributed among two electricity and three seafood production.

Table 3.5 Aggregated macro 2013 SAM for Scotland (in £million) (Based on Katris et al., 2019)

	Activities	Labour	Capital	Household	Corporation	Government	Investment-Savings	Rest of UK	Rest of World	Total
Activities	57338.9	-	-	55642.9	-	31665.0	14318.8	38981.9	28151.3	226098.7
Labour	69339.4	-	-	-	-	-	-	3851.5	168.1	73359.0
Capital	49101.4	-	-	-	-	-	-	-	-	49101.4
Household	-	73359.0	10197.0	-	21682.2	22505.8	-	911.9	2648.8	131304.7
Corporation	-	-	32527.2	7788.0	-	16742.5	-	1248.1	-1954.3	56351.4
Government	5752.1	-	6377.3	32330.1	5981.2	-	2407.1	12122.6	522.3	65492.6
Investment-Savings	-	-	-	8160.9	28688.0	-5420.6	-	-9377.4	977.0	23380.9
Rest of UK	28797.1	-	-	19002.2	-	-	3775.6	-	317.4	51892.3
Rest of World	15769.7	-	-	8380.7	-	-	2526.5	4153.9	-	30830.7
Total	226098.7	73359.0	49101.4	131304.7	56351.4	65492.6	23380.9	51892.3	30830.7	

The sector’s cost structures are shown in Figure 3.3. An activity’s output is produced by inputting value-added (labour and capital) and intermediate inputs, together with producer taxes or subsidies (shown as negative taxes in Figure 3.3) imposed by the government. Differences in cost structure are important in determining the way that a sector’s competitiveness is affected by variations in input prices, particularly for capital and labour.

Small sectors will tend to have production structures that differ from the average by a greater extent than do large sectors. This means that their competitiveness will tend to respond more strongly to the changes in input prices that are generated by exogenous shocks. Like the electricity sectors, fishing and aquaculture are relatively capital intensive, while fish processing is relatively labour intensive. Intermediate input demand linkages also create a channel through which a shock in one sector is transmitted to other sectors. Among the three seafood sectors, fishing and aquaculture are important intermediate inputs for the fish processing sector while aquaculture needs relatively more electricity as a production input.

Both electricity sectors require a large amount of electricity as an intermediate input, mainly because of conversion losses (about 45%), distribution losses and energy industry use (about 6%) (Scottish Government, 2020a). Higher conversion losses offshore also explains why the electricity input share is higher for OWF than other electricity sector. The other difference in production inputs between OWF and other electricity sector is the share of capital. As the UK content on capital expenditure is limited on OWF, its capital input share is relatively small (RenewableUK, 2017).

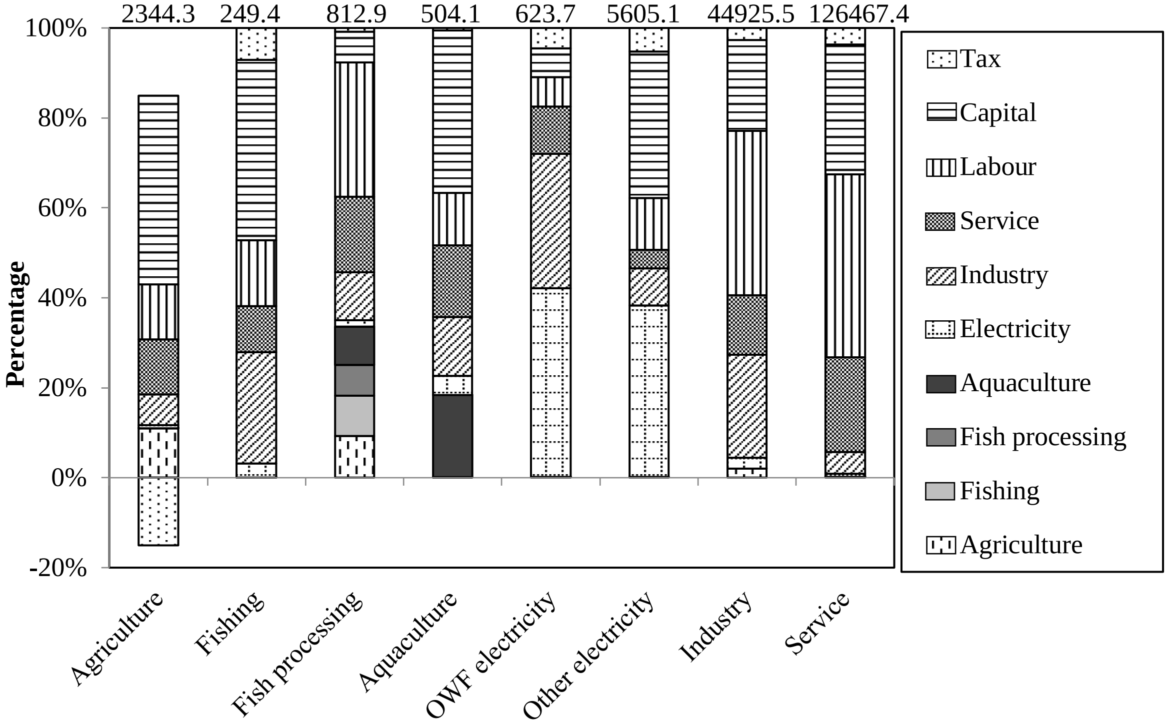

Figure 3.3 Production input intensity of production activity sectors with total output above (in £million). (Data source: Allan et al., 2019; Katris et al., 2019)

In the SEMM model, eight production activities produce seven commodities to be sold in both domestic and foreign market: the two electricity production activities combine to generate a single electricity commodity. The demand for commodities is shown in Figure 3.4, including intermediate input, household and government consumption, investment on commodities, and export. It should be noted that exports accounted for more than two thirds of domestic output for three seafood commodities while for electricity more than half is demanded by intermediate input (corresponding with Figure 3.3).

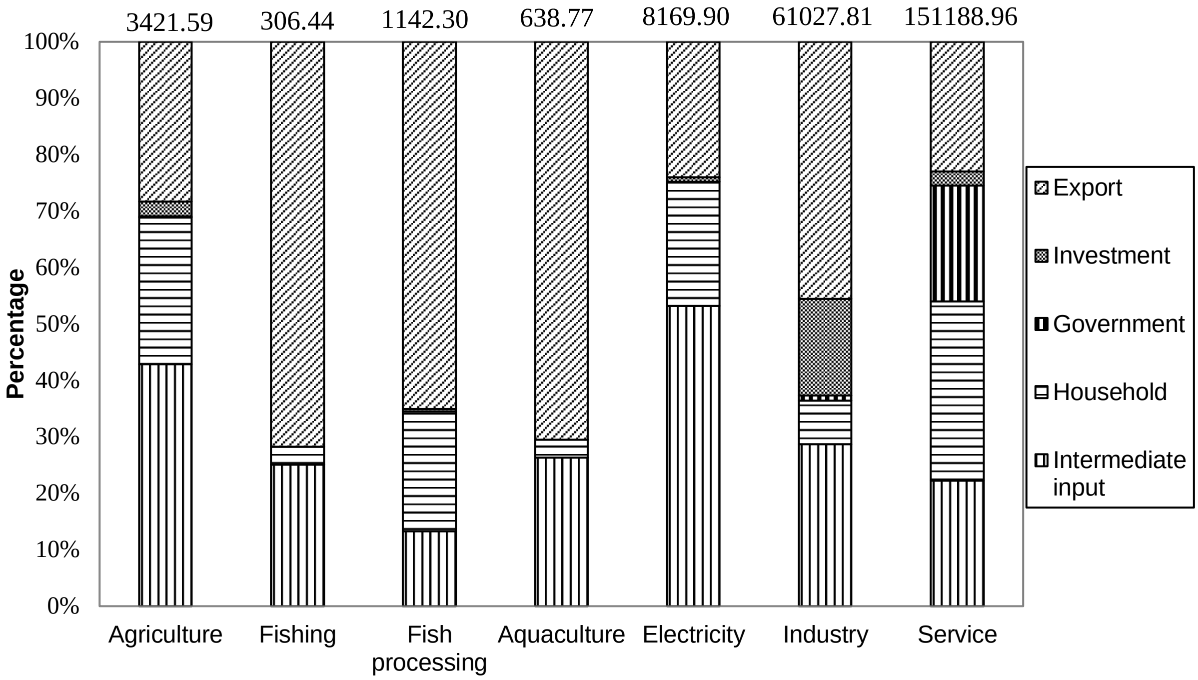

Figure 3.4 The composition of demand for each commodity between different demands with numbers at the top of the bars are the total value in millions of pounds (Data source: Allan et al., 2019; Katris et al., 2019; Scottish Government, 2020).

The SAM distinguishes household income quintiles, with weekly income increasing from HH1 to HH5. Households receive income from factor returns, transfers from the government, other domestic institutions (corporations), and the rest of the world. As shown in Figure 3.5, lower income household groups (HH1 and HH2) receive a greater share of their income from government transfers, in the form of welfare and state pensions, while household groups with higher income (HH3, HH4 and HH5) are relatively more dependent on wage and capital income. Meanwhile, household disposable income is net of personal income tax, savings, and remittances to the rest of the world. Household consumption comprises only a small share in the total commodity demand, especially for fishing and aquaculture (Figure 3.6). Generally, household commodity consumption increases with higher income except for more evenly distributed electricity consumption.

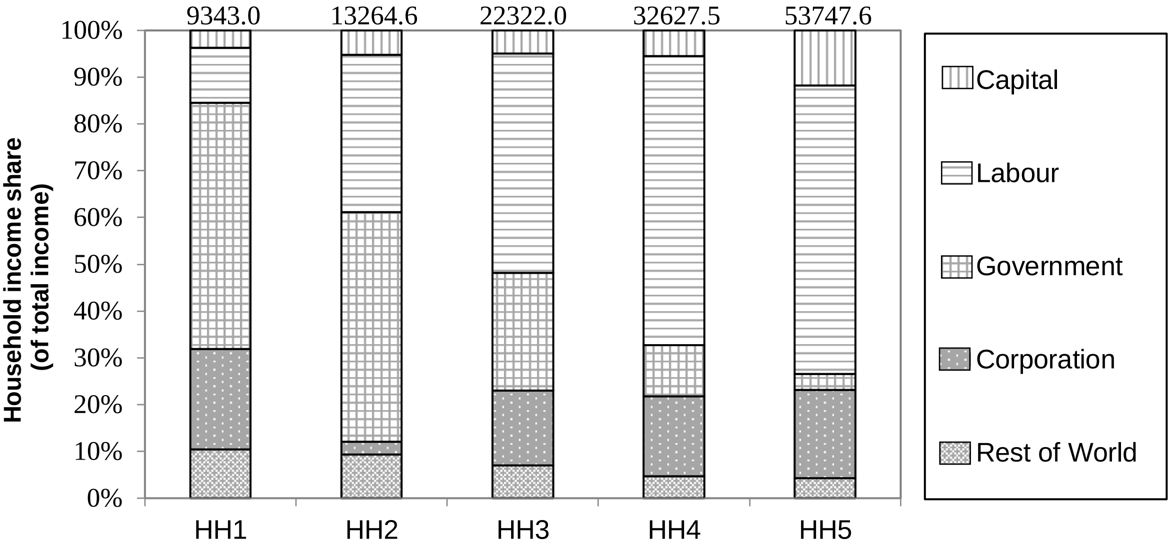

Figure 3.5 The share of different income sources for household quintiles with income increasing from HH1 to HH5 with mean annual income shown at the top of each column (in £million). (Data source: Katris et al., 2019)

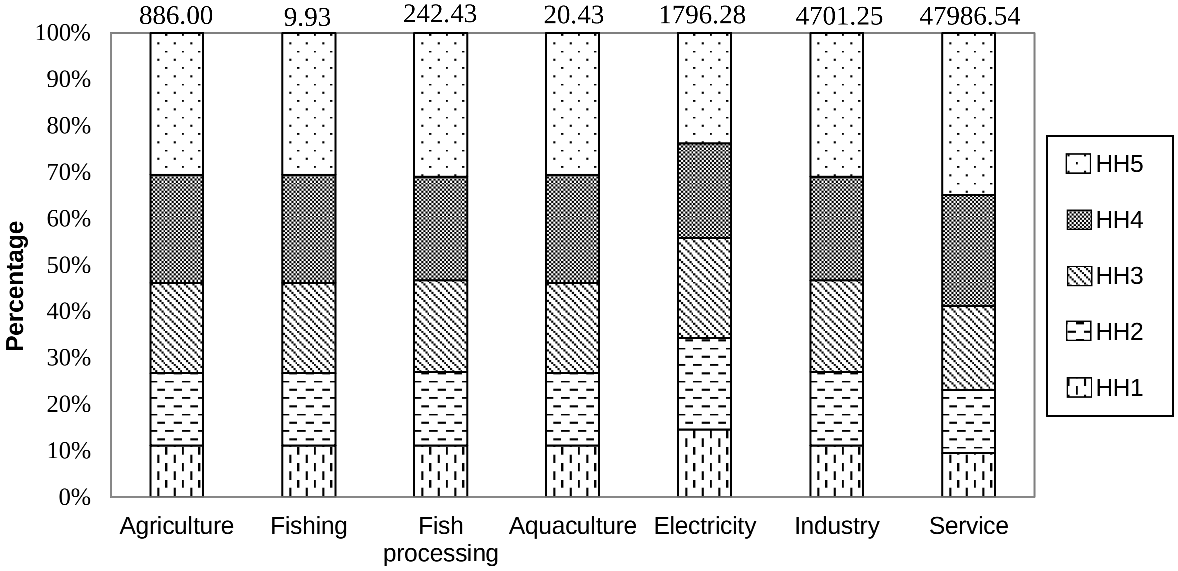

Figure 3.6 Shares of commodity consumption between household groups; numbers at the top of the bars are the total value in millions of pounds (Data source: Allan et al., 2019; Katris et al., 2019; Scottish Government, 2020).

Government receives most of its income from taxes, capital rental and transfers from other institutions, while spending on consumption commodities and transfer to other domestic institutions. The difference between income and expenditure is the budget deficit, as shown in Table 3.5, which is financed through borrowing from the domestic capital market. Savings by households, corporation and government are collected in the saving row equals to the investment column (Table 3.5). There is only one investment column in the SAM (mainly due to data limitation) so there is no differentiation on the type of capital, suggesting the homogeneity of capital.

All these production activities, consumptions and accounts mentioned above are incorporated in the SEMM by the suite of microeconomic functions described below.

3.2.1.2. Choice of functions

Production side

The basic CGE model structure employed follows the version described in Section 3.1.2, with the specific choices of functional forms for all elements shown in the corresponding position in Figure 3.7. To allow more flexibility, the production functions are mostly the CES function, except for intermediate inputs which are combined in a fixed ratio of disaggregated inputs using a Leontief function to avoid a more complicated nested structure of the model. There are two electricity production activities producing one composite commodity, i.e. electricity. The default setting for the aggregation into one composite commodity is as a fixed share, but a CES function is available as an alternative choice to allow a more competitive OWF electricity activity to increase its share of total electricity generation. The default setting is adopted to avoid the replacement of OWF electricity by other electricity under the ‘higher cost of OWFs’ assumption in first application. It is then relaxed with CES function in second and third application where a substantial OWFs expansion is assumed.

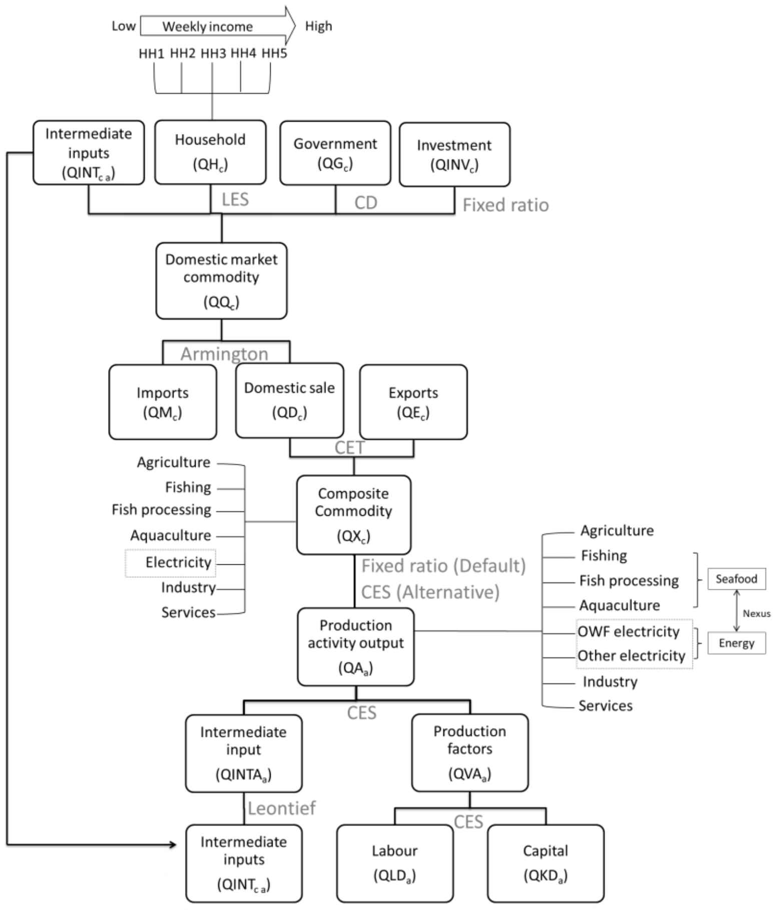

Figure 3.7 Basic structure of the SEMM

Consumption side

For consumers, households receive income in factor payments, and then pay direct taxes to government (based on tax rates) and save (based on marginal propensities to save). Then household spend their disposable income on commodities represented by LES function, which is derived from Stone-Geary utility function subject to a household budget constraint (Stone, 1954). Given prices and incomes, the LES functions define households' real consumption of each commodity by identifying the supernumerary household income that ensures a minimum level of consumption. Household welfare is measured by the Hicksian equivalent variation (EV) in income which measures the income needed to make households as well off in the new equilibrium as evaluated at benchmark prices.

Government revenues consist of all taxes and transfer payments from other institutions and the rest of world. Total government expenditures comprise consumption on commodities determined by a Cobb-Douglas utility function, transfers to other institutions (e.g. social welfare to households), and savings.

Due to the model assumption of one type of non-sector specific capital, which is used in all sectors of the economy, the model need not incorporate any explicit investment behaviour. The disaggregation of investment into demand for composite commodities is defined as the base-year quantity multiplied by an adjustment factor.

All the functions assumed in the model are summarised in the Table 3.6 below.

Table 3.6 Summary of model functional forms choice

Economic elements	Functional forms	Relevant equations in Table A2	Justification	Reference
First level of production activity (QA_a)	CES	Equation 1 - 3	Enabling producers to substitute production inputs	Löfgren et al., 2002
Second level of production activity – Value added (QVA_a)	CES	Equation 4 - 6	Enabling producers to substitute factors	
Second level of production activity – Intermediate inputs ($QINTA_a$)	Leontief	Equation 7 - 8	Simplifying the model structure	
Aggregation of commodity (QX_c)	Fixed ratio (default)	Equation 9 - 10	Avoid replacement of offshore wind electricity with higher cost of OWF assumption	
	CES: Application 1 - sensitivity analysis; Application 2, 3	Equation 11 - 14	Enable offshore wind electricity to be competitive due to decreasing cost of OWF assumption	

Table 3.6 Continued Summary of model functional forms choice

Economic elements	Functional forms	Relevant equations in Table A2	Justification	Reference
Exports (QE_c)	CET	Equation 15 - 18	Allow imperfect substitutability between exports and domestic commodities	Löfgren et al., 2002
Imports (QM_c)	Armington	Equation 19 - 22	Allow imperfect substitutability between imports and domestic commodities	Armington, 1969
Households ($QH_{c,h}$)	LES	Equation 23 - 25	Allow more substitutability; distinguish normal and luxury goods	Stone, 1954
Government (QG_c)	Cobb-Douglas	Equation 26 - 27	For simplified government	Hosoe et al., 2010
Investment-Savings ($QINV_c$)	Fixed ratio	Equation 28	For simplification	Löfgren et al., 2002

Model closure

The model needs to be closed in the sense of the need to determine which variables are exogenous and which are endogenous to the model. The choice of closure rules has significant implications on the behaviour of the agents and defines the solution in a CGE model. The combination of these closure rules more closely mimics the real world and better explores the role for complementary policies (Löfgren et al., 2002).

For **factor markets**, the model has three factor closure available for different research objectives (Table 3.7). As mentioned before, static SEMM provides impact assessments by comparing the before- and after-shock equilibrium conditions but no estimation of adjustment path along an optimal time path between two equilibria (dashed line in Figure 2.1). To illustrate the range of possible dynamic responses using a static CGE model, different factor mobility/closure could be applied (Waters and Seung, 2010).

The first factor closure is referred as 'short-run' closure where labour is assumed to be fully mobile between sectors while capital is fixed at its base-year value. Mobile labour is able to move between sectors in response to changes in relative price which is a uniform, flexible, market-clearing wage to balance labour supply and demand. It leads to an equalisation of the increase or decrease in the wage rate across all sectors. The fully mobile labour under fixed supply assumption tracks marginal adjustments to the distribution of the labour force across sectors and those who can most easily shift between sectors would be expected to be those that do. In the context of OWFs and fishing activities, fishermen could apply their knowledge and skills of the fishing industry in an expanding renewable energy sector. For example, fishermen in Gulf of Mexico have moved from work on oil and gas to help develop machine shops, service companies, and transportation services (Austin et al., 2002; Perry et al., 2012). The 'short-run' closure is therefore a relatively short-term view of local economic conditions in which labour adjusts quickly while capital stocks do not.

The second one is 'long-run' closure which refers to fully mobile labour and capital between sectors. As mentioned in the above section, the capital is homogenous and can be flexible, given enough time to adjust. Such flexible capital corresponds with a crowding-out effect: production sectors could divert capital from other sectors to expand production through pricing up the relative price (Hu, 1972; Mercure et al., 2019). Flexible capital is possible in reality through depreciation: at initial equilibrium, investment just covers depreciation; when applying a shock, the capital rental becomes higher in one sector than others, no net investment in low capital rental sectors so that capital decreases while new investment goes to high capital rental sector and capital accumulates; at new equilibrium, capital rental reaches same across sectors and capital is reallocated. As the SEMM is a comparative static model, it is not able to show the above adjusting process period by period but rather present the final status of such capital movement.

The third one is 'extra-long-run' closure which is sometimes called a 'steady-state' closure (Francois et al., 1999). The impact assessment under the previous two assumptions is limited by the fixed capital stock whereas the extra-long-run capital accumulation relaxes the capacity constraint. In this case, the amount of capital stock in the current period is determined by the depreciated amount of the initial investment and the price of capital is assumed to be at a profit rate. Increases in the return to capital caused by a shock to the economic system would induce an increase in capital stock, thereby driving the level of investment increase at the same rate[6] (Allan et al., 2014a). In this way, the expansion of the capital stock generates an endowment effect that can be thought of as capturing the dynamic effects of the shock.

Table 3.7 Summary of model factor market closure assumptions

Factor	Closure	Assumption	Relevant equations in Table A2	Exogenous variables	References
Labour	All three	Fixed labour supply	Equation 35	Labour supply (QLS)	Löfgren et al. (2002)
Capital	Short-run	Fixed capital sector demand	Equation 36	Capital demand (QKD_a)	Löfgren et al. (2002)
	Long-run	Fixed capital supply		Capital supply (QKS)	
	Extra-long-run	Flexible capital stock		Capital rental (WK)	Francois et al. (1999), Gilbert and Tower, (2013)

It should be noted that because SEMM is a comparative static model, time preference for investments is not captured (Banse et al., 2013). There are no dynamics in the model. This means that although the model can be used to consider the impacts from short-run, long-run and extra-long-run perspective, the model does not explicitly consider the evolution of economic changes through a sequence of points in time. The three different closure rules refer to different conceptual equilibrium states related to different levels of capital mobility (Haddad et al., 2010). Structural changes are

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[6] As the SEMM is static, investment behaviour has no influence on capital accumulation but is considered as replacing a chunk of capital. It is assumed that the investment is being funded through international capital markets.

captured only through the evaluation of a reallocation of resources which is the main concern in the nexus thinking so that these three different closures are corresponding to cover all possible nexus assessment. In other words, the SEMM tries to account for some structural characteristics of the economy, which is the different mobility of capital under different assumptions (Thurlow, 2004). Even though the SEMM is a comparative static model, it is conventional to distinguish three separate conceptual economy states, which could be also associated with three conceptual time periods if necessary[7].

For the **current account**, it is assumed that a flexible exchange rate adjusts in order to maintain a fixed level of foreign savings. The choice of this closure is determined by flexible exchange rate system in Scotland.

In the **government account**, the tax rates and government consumption are held constant. This closure is adopted because tax rates and government consumption are normally politically determined and thus hold as exogenously fixed. The reason of this choice is based on government policies so that the model results are more applicable to policy.

For **investment-saving account**, investment-driven closure is chosen for short-run and long-run assumption. There are two reasons to choose the investment-driven closure. First, as the short-run and long-run assume fixed capital (i.e., no capital accumulation), it is more reasonable to fix the total investment to make savings adjust to maintain the level of investment. Second, as discussed in Section 3.1.2, compared to saving-driven closure, investment-driven closure better measures the full welfare change, which is one of the research questions to be solved in the thesis. When it is extra-long-run closure, the model takes investment endogenous to accord with the flexible capital, where the investment is assumed to be funded through international capital markets. In this case, investment is determined endogenously by changes in domestic and foreign savings.

Therefore, the results of counterfactual simulations could be interpreted under above closure rules as representing the economic effect of a certain shock for a given level

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[7] Although there is no clear evidence on how long it takes for an economy to reach a new equilibrium following a shock, econometric evidence in favour of short-run equilibrium established in about 1 – 2 years (Cooper et al., 1985); the long-run is about 2 – 5 years (Seung and Waters, 2010); the extra-long-run might take 10 or 20 years (Narayan, 2003).

of foreign savings, investment, provision of government services, taxes, and different mobility of capital.

Finally, the GDP deflator (PGDP) is chosen as the model's numeraire which shows the model assumes there is no interaction between monetary and real economies. The model is also homogenous of degree zero in prices, implying that a doubling of all prices does not alter the real allocation of resources.

In summary, the CGE model is built by a set of simultaneous equations. These equations define the behaviour of the different agents in the model. All the equations included in the model are listed in the Appendix 1.

Table 3.8 Summary of model macro closure assumptions (Based on Löfgren et al., 2002)

Model closure	Assumption	Relevant equations in Table A2	Exogenous variables
Government	Fixed tax rate	Equation 34	All tax rate (TA_a) Government consumption (EG)
Current account	Fixed foreign savings	Equation 35	Foreign savings ($FSAV$)
Saving-investment	Fixed investment	Equation 36	Investment adjust factor ($IADJ$)
	Flexible investment (extra-long-run)		Saving rate (DMPS)
Price numeraire	Fixed GDP deflator	Equation 37 - 38	PGDP is independent macroeconomic variable

3.2.1.3. Assumptions of parameters

The primary source of elasticity used in SEMM is AMOSENVI, which is also a Scotland-based model (Allan et al., 2014). However, for sectors like fish processing and aquaculture, there are no existing published elasticities. The model therefore uses unvarying elasticities across all production activities and trade, except the elasticity of export transformation (Table 3.9). The elasticity of export transformation for electricity and three seafood commodities is less than one to avoid over sensitive impacts given that they are small sectors. The construction of the model takes explicit account of the fact that the elasticities cannot be determined with certainty as extensive econometric works are required to identify all elasticities. Sensitivity analysis is therefore conducted to test the validity and robustness of estimated parameters and the implications of the model results (Hertel et al., 2007). Sensitivity analysis can also provide the confidence interval of the model simulation results (Hosoe et al., 2010). The outcome of sensitivity analysis is a distribution of model results, which lay the foundation for answering the research question of this thesis. Under this circumstance, constant elasticity across all production activities could be an optimal solution.

Table 3.9 Production function behaviour parameters (based on Allan et al., 2014; Lecca et al., 2014)

	Elasticity of Substitution			
Production Sectors	Elasticity of aggregate input (σ_a^a)	Factor substitution elasticity (σ_a^{va})	Elasticity of export transformation (σ_c^t)	Armington substitution elasticity (σ_c^q)
Agriculture	0.3	0.3	2	2
Fishing			0.5	
Fish processing				
Aquaculture				
OWF electricity				
Other electricity				
Industry			2	
Service				

Income elasticities help distinguish the commodity into normal and luxury goods for households, which contributes to a more detailed measure of distributional impacts across poor and rich households. For example, an income increase may lead to an increase in service consumption for poor households for whom service is a luxury good, whereas richer households may reduce the consumption share since service is considered a normal good to them. All income elasticities used in the model are estimated based on published works identified in Table 3.10. Most studies only provide average income elasticities so what is used in the model are adjusted using two general income elasticity trends. First, the size of income elasticities should be a decreasing trend from lowest to the highest household incomes (Jussila et al., 2012; Meier, 2010). Second, the variation in income elasticities is relatively low across the different household categories, between 0.02 and 0.2 around the central value (Jussila et al., 2012). The income elasticities used in SEMM are therefore mainly estimated based on the existing literature and assuming low variation across households.

In SEMM the agriculture, fishing, fish processing and electricity commodities are treated as normal goods for all households with the assumption that their expenditure will increase when income increases. Among the three seafood commodities, the aquaculture commodity is considered a luxury good for lower income households and a necessity for highest income households (HH5) due to aquaculture fish being more expensive than capture fish (Delgado et al., 2003; OECD, 2018) and higher income households tend to consume more seafood (DEFRA, 2017; Kearney, 2010). Service and Industry are also assumed to be luxury goods across all households except HH5 (the highest income group).

The Frisch parameter determines the subsistence consumption level of households in the LES function, which can be considered as necessary quantities of different commodities required by each household for living. The Frisch parameter used in this model is based on the general statement of applicable relationship between the parameter and income intervals given by Frisch (1959) that a falling absolute Frisch parameter is assumed with increasing income. To confirm the validation of the Frisch parameter, one approach involves using a flexible specification which extends the logarithmic form used by Lluch et al. (1977), whereby the variation in the Frisch parameter (φ) with household income (y) is given by

$$\log(-\varphi) = a - \alpha\log(y + \theta) \tag{1}$$

The value of a, α and θ can be obtained from the empirical literature. This model estimates three parameters based on the work by Creedy and Dixon (1998). The calculated value used in the model is shown in Table 3.10. Both income elasticities and the Frisch parameter allow differentiating representative households because they are specific to each household. This means that the budget decisions of each household are based on their income and commodity prices, which aids the analysis of distributional impacts across households possible within CGE models (Jussila et al., 2012).

Table 3.10 Consumption function behaviour parameters

	HH1	HH2	HH3	HH4	HH5	Reference
Income elasticities ($e_{c,h}$)						
Agriculture	0.35	0.30	0.25	0.10	0.05	0.2 (De Agostini, 2014; Lechene, 2000)
Fishing	0.70	0.60	0.50	0.40	0.30	0.27 (De Agostini, 2014; Lechene, 2000) 0.54 – marine fish (FAO, 2017) 0.36 (Jussila et al., 2012)
Fish processing	0.70	0.60	0.50	0.40	0.30	Assumed
Aquaculture	1.20	1.17	1.15	1.12	0.90	1.1-1.22 (FAO, 2017)
Electricity	0.80	0.70	0.50	0.30	0.20	0.2-0.9 (National Infrastructure Commission, 2017)
Industry	1.15	1.13	1.10	1.08	0.90	Assumed
Service	1.15	1.15	1.10	1.05	0.90	Assumed
Frisch parameter (φ)						
Frisch	-7.27	-5.34	-3.07	-1.92	-1.20	Creedy and Dixon (1998) $\log(-\varphi) = a - \alpha \log(y + \theta)$ $(a = 18.566, \alpha = 1.719, and\ \theta = 10575)$

The basic structure described above along with assumptions of functional form and parameters are at the centre of the SEMM that forms the basis in this thesis. The following sections explain the further development of the modelling frameworks for analysing the energy-food nexus beyond the macroeconomic linkages included in the standard CGE model.

3.2.2. Modelling framework for analysing competing use of marine resources

The expansion of OWFs could result in displacement from existing fishing grounds comparable to the way that the development of biofuel potentially diverts land from food production (e.g. Arndt et al., 2012; Ferreira Filho and Horridge, 2014; Timilsina and Mevel, 2013). Therefore, in a manner similar to agricultural land, the marine area could be treated as a potential production factor, additional to labour and capital. This means that the existing SEMM is augmented with an innovative production factor, labelled marine resource, that aids in the analysis of the spatial trade-offs between the expansion of OWFs and fishing activities. This represents a major improvement in the SEMM model.

3.2.2.1. Initialization and valuation of marine resource

The general idea underlying the marine resource specification is similar to the specification of land as a production factor in a SAM. However, use of a scarce marine resource is not a traditional production factor accounted for in a SAM. For the purpose of this study, a number of assumptions are made to initialise the marine resource module in the SAM on which the SEMM model is parameterised.

First, the fish landings are assumed to be evenly distributed across Scotland's marine area to simplify the reallocation of marine resource, since the SEMM has no spatial dimension so cannot differentiate the values of different fishing areas. Second, marine resource use is assumed to be competitive only between the OWF electricity and fishing production sectors. Therefore, the requirement for additional marine resource from the expansion of OWFs is met by the fishing sector, representing the trade-offs between these two sectors from the energy-food nexus perspective. Any spatial overlap is expected to occur mainly in offshore areas where aquaculture and fish processing do not take place, i.e., there is no marine resource trade-off with these sectors. Last, the total supply of marine resource is fixed by the available marine area.

In order to determine the economic trade-offs, the monetary value for the use of the marine resource must be determined. The value of a given area of ocean space varies depending on its characteristics and uses (Kite-Powell, 2017). In the model, the valuation of marine resource is derived from payments made by maritime activities to use the marine area. For the fishing sector, the valuation is the cost of purchasing fish quota, which is one of the main operating costs for fishermen (Seafish, 2018). The value of marine resource for fishing is equal to 30% of the landed fish value, which is generalised from the fish quota prices (Hatcher et al., 2002). For offshore wind electricity, the value of marine resource is the marine activity licence fee paid in order to use the seabed, which is assumed in the model as 1% of total revenue from offshore wind electricity (Scottish Government, 2018c). The initial payments determine the initial share of the resource going to the two sectors: OWFs take 7.7% as only a very small amount of Scottish sea area is currently occupied by OWFs, the fishing sector uses 92.3% since fishing activity is assumed to be evenly distributed across the entire marine area. A new marine resource account is created in the SAM to record the payments on marine resource. A new factor column and a matching row account for marine resource have been disaggregated from the 'capital' account in the fishing and offshore wind electricity sectors. The return of the marine resource is separated from the return to capital. The marine resource is assumed to be solely owned by the government.

3.2.2.2. Marine resource allocation module

Consideration of the use of the marine resource adds another level in the nested production structure and allows more flexibility between input factors, as shown in Figure 3.8. A CES function is assumed between marine resource ($QMRD_a$) and the capital-labour composite ($QKLD_a$), allowing a degree of substitution between marine resource use and labour and capital inputs:

$$QVA_a = \alpha_a^{va} \times [\delta_a^{va} QMRD_a^{\frac{\sigma_a^{va}-1}{\sigma_a^{va}}} + (1-\delta_a^{va}) QKLD_a^{\frac{\sigma_a^{va}-1}{\sigma_a^{va}}}]^{\frac{\sigma_a^{va}}{\sigma_a^{va}-1}} \quad (1)$$

The allocation of the marine resource and capital-labour composite is based on their relative prices, where $WMRD$ is the economy-wide marine resource price, $WMRDIST_a$ is the sector-specific marine resource price, and $PKLD_a$ is the sector-specific capital-labour composite price:

$$\frac{WMRD \times WMRDIST_a}{PKLD_a} = \frac{\delta_a^{va}}{1-\delta_a^{va}} (\frac{QKLD_a}{QMRD_a})^{1-\frac{\sigma_a^{va}-1}{\sigma_a^{va}}} \quad (2)$$

where the subscript a applies only to the fishing and OWF electricity sector.

Therefore, a change in sectoral outputs affects relative factor prices and factor intensities. When the OWFs expand in the model, a proportion of the marine resource is re-allocated through the price adjustment mechanism under a competitive market in the model. The marine resource input is assumed to be substitutable with the capital-labour composite through the CES function because the use efficiency of marine resource is related to investment in offshore wind turbines. The size of the substitution effect depends on the cost and the availability of technology to improve the capacity of each wind turbine, so that a unit area of offshore wind project could support larger turbines with higher capacity by using more labour and capital. It is reflected in the value of the substitution elasticity (σ_a^{va}). That is to say, for example, if the elasticity is high (σ_a^{va}), when the OWFs are expanding, there would be larger turbines (input more labour and capital to develop the technology) built with little expansion in space (high substitution effect), resulting less marine resource constraint on the fishing activity.

Since this elasticity is unavailable, it is therefore necessary to conduct the sensitivity analysis to test the robustness of results. The initial value of this elasticity is set at 0.3 representing a situation where marine resource is complement of the capital-labour composite.

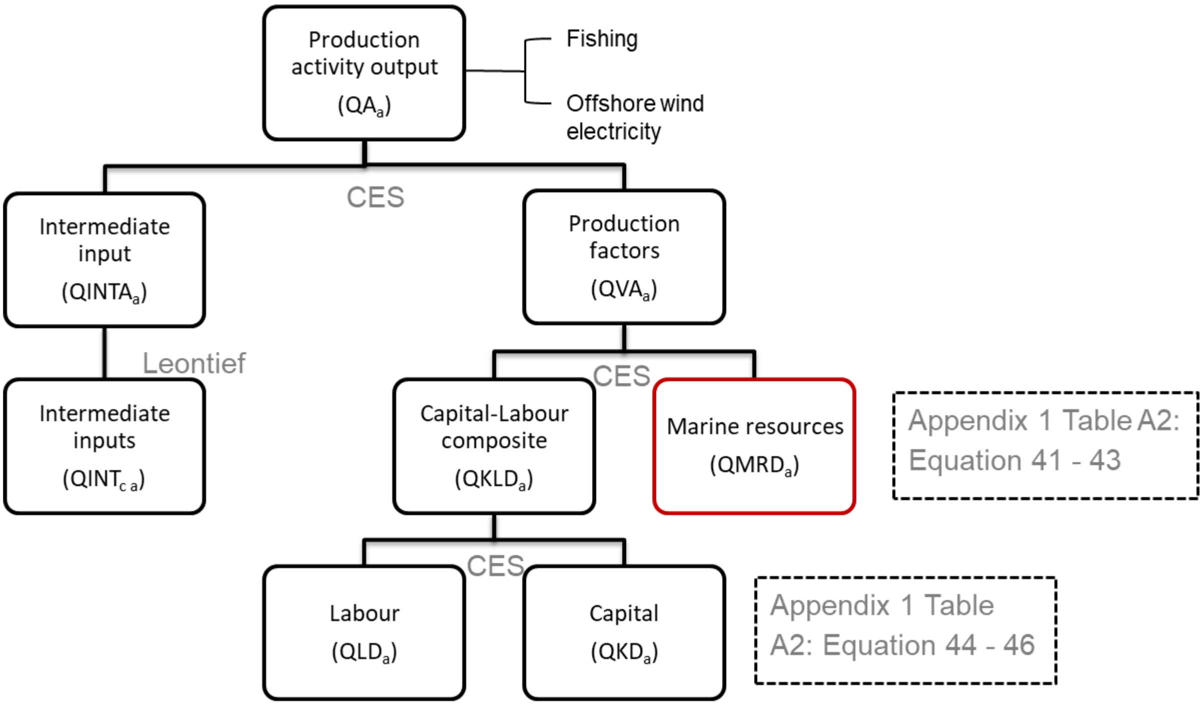


Figure 3.8 Extended production nested structure with marine resource allocation module in SEMM

The marine resource allocation module is established to visualize the spatial conflict between OWFs and fishing activity in the SEMM. Together with marine resource allocation module and the production structure (as shown in Figure 3.8), the mechanism between the energy-food nexus of OWFs and fishing sector and the marine resource market have been explicitly captured. The marine resource is one of the primary production factors for OWFs and fishing production, which means that the infinite expansion in both sectors will be constraint by the fixed supply of marine resource. Under the condition of OWFs expansion, the allocation of marine resource is taken to operate as a competitive market so that the OWF electricity sector bids up the economy-wide marine resource price. The payment for the use of marine resource is set as a rental which is flexible to clear the market. Some marine resource is released by the fishing sector, which represents the conversion of fishing grounds into OWF areas. This then increases the production cost of the fishing sector and the subsequent price of fish. Ultimately, changes in fish supply would impact on seafood production, on a households' consumption choices and their wider welfare.

The aim of disaggregating the marine resource factor from capital is to highlight the direct linkage between development of OWFs and maintenance of the fishing activities in the marine environment. Since the impacts of OWFs on seafood production are analysed more from a biological and ecological side, it is important to have an economic indicator to allow transfer of these impacts into economic linkages. The competition for marine resource provides an attempt to assess the economic impacts of displacing existing fishing activities by OWFs.

3.2.3. Modelling framework for incorporating natural capital

3.2.3.1. 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, which 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; natural capital provides ecosystem services considered as non-monetary market goods and therefore is 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, in line with the guidance of 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, fish harvesting depends on the availability of fish stocks but also high-quality habitat (Guerry et al., 2015). In the context of this thesis, the actual production input is the fish harvested (ecosystem services) provided by the fish stock (natural capital) in the marine environment, resulting in feedback loops between the economy and natural environment.

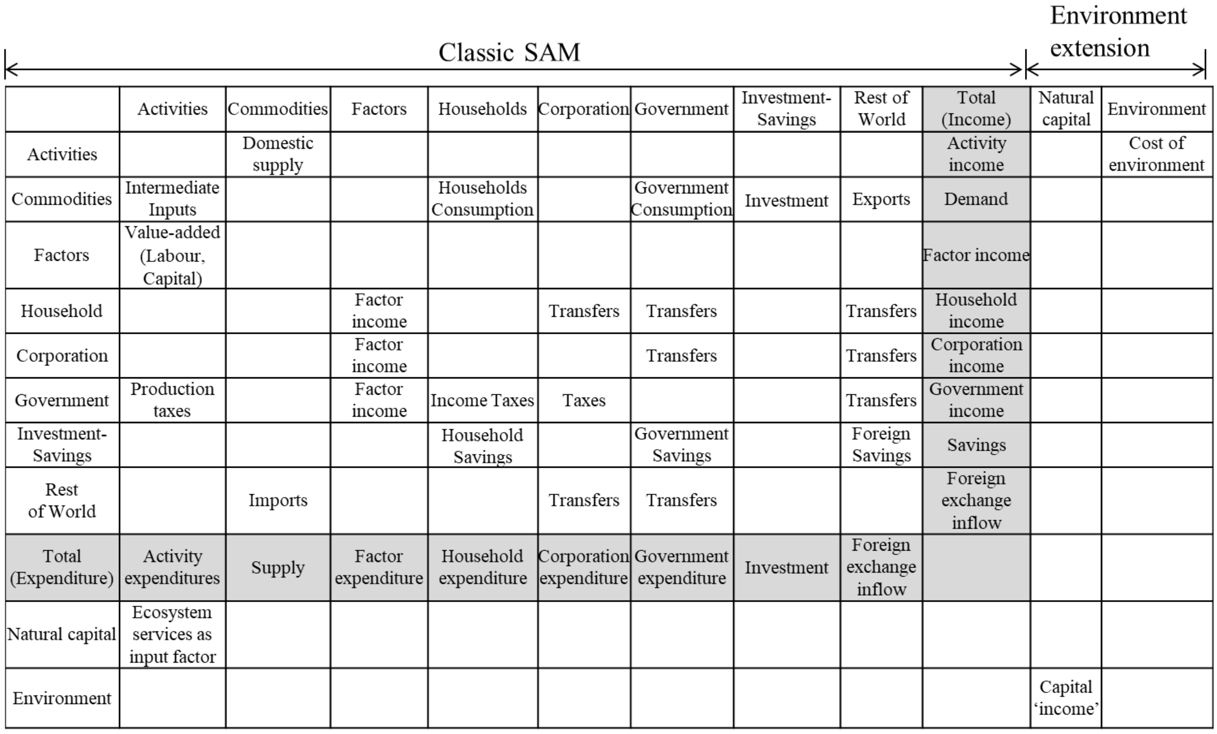
The next step is accounting and valuing natural capital and ecosystem services using the methodology proposed by ONS (2019a). The natural capital accounting framework includes assessment of both assets and flows. The ecosystem service flow valuation is based on the resource rent which can be interpreted 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). Table 3.11 shows the annual monetary value of ecosystem services (i.e. flow) account in 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 is 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 happens in 2014, which is 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, 2019f). Therefore, the Scottish fish asset value used here is assumed to be 37% of UK fish asset value.

Table 3.11 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, 2016, 2018, 2019a, 2019b; 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. In order to allow natural capital 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., 2016b; 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 3.9. 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 it also means depletion of the corresponding natural capital in the environment. Hence, there is one more cell between the environment column and the activity row that is required to represent the cost to the environment for supplying the natural resources. 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 3.11.



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

3.2.3.2. Linkages between the CGE model and a natural capital module

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. The classic CGE model is capable of analysing the impacts of the expansion of OWFs on fishing activity at the economy level. It has an economy-wide framework, having multiple production activities, enabling substitution of inputs in production and commodities in demand, and adjusting prices to make supply equal to demand for both production factors and commodities under the equilibrium condition as described in Section 3.1.1.2. However, the classic CGE model does not cover the linkages outside of market interactions, such as the profound impacts on fish stock from the economic side; nor does it include ecological processes, such as potential benefit to fish stocks due to the artificial reef effect of OWFs. Linking the environment and the economy-wide CGE model can overcome these shortcomings by enabling comprehensive analysis of the two-way linkages within and outside the economy. Figure 3.10 shows a schematic diagram integrating the environment within a CGE model.

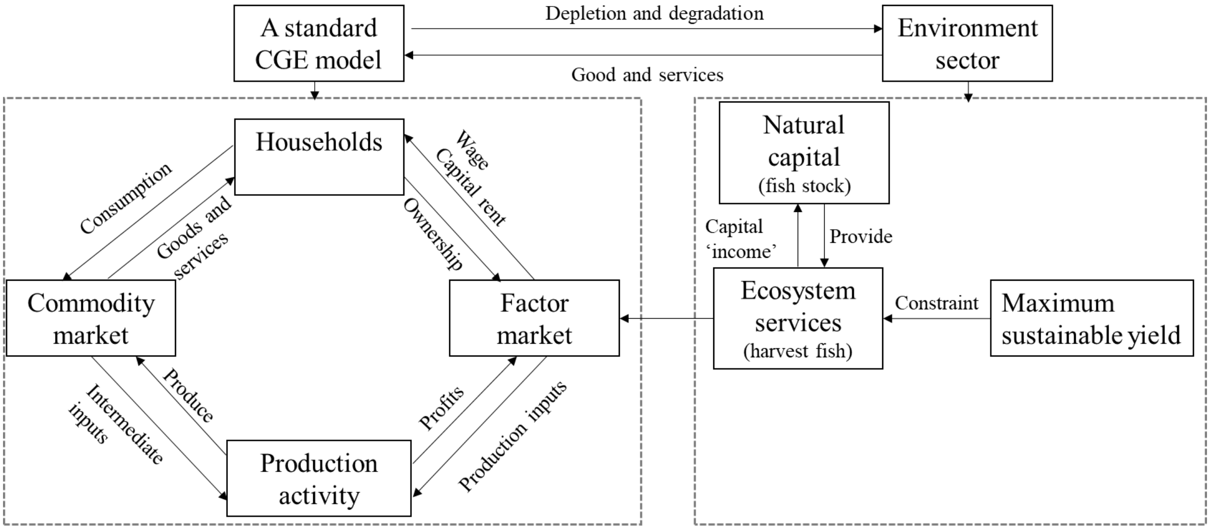


Figure 3.10 Flow chart of the structure of the CGE model with environment as a new sector (Adapted from Allan et al., 2018)

The natural capital module is linked with the SEMM model, allowing the economic processes to affect fisheries productivity and output and ultimately the level of fish stock. Fishing sector production demands not only physical capital and labour like other sectors, but also specifically harvesting fish as an input. In this SEMM-Natural Capital model, the harvested fish used as production input represents an ecosystem service, which is provided by natural capital, i.e. fish stock (Figure 3.11).

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 3.11 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., 2016b; 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) while the fishing effort E is a function of corresponding 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. Any changes from the economy would impact both variables and can be tracked through these equations. For example, reduced demand for fish from households would result in the production from fishery-related sectors decreasing, resulting in a lower amount of fish harvested from the marine environment, thus conserving of the fish stock. On the other side, any changes in fish stock would affect the rest of economy. An increase in fish stock (increase in B_0 refers to $\alpha > 1$) leads to an adjustment in fishing efforts and thus reallocates labour and capital among sectors, and eventually changes the production cost for not only the fishing sector but also other sectors. In this way, the SEMM-Natural Capital model considers the state of the natural assets and the ecosystem services that they produce to ensure a more holistic and comprehensive representation of the natural environment is linked with the economic system.

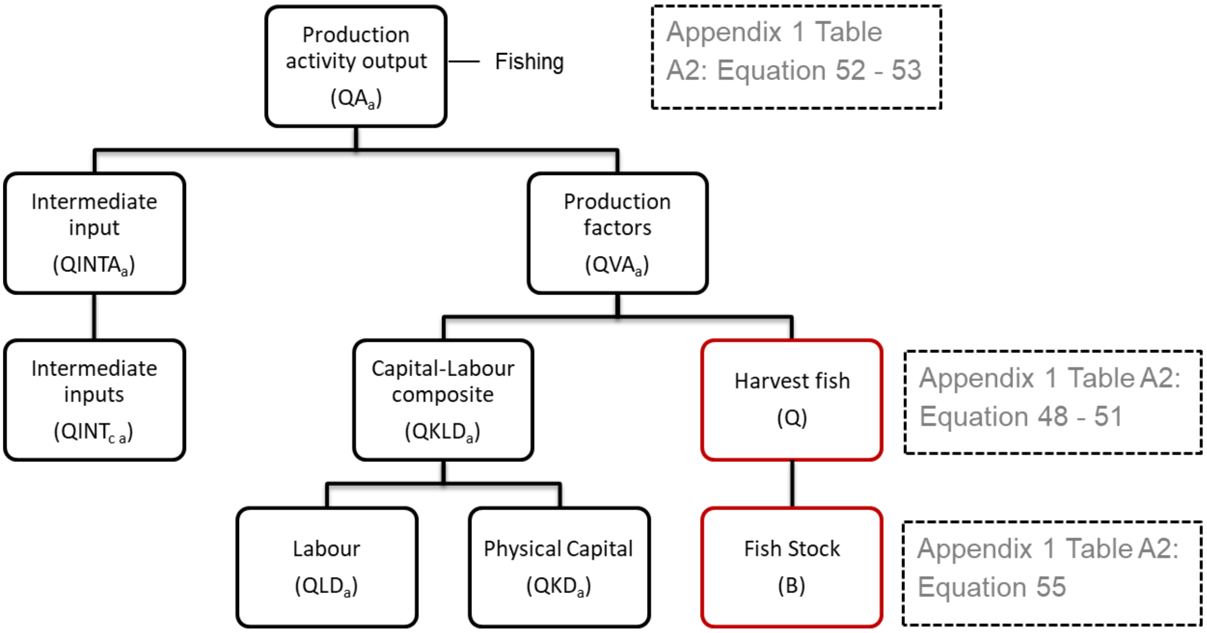


Figure 3.11 Extended production nested structure with natural capital in SEMM

3.3. Conclusion

In general, this chapter fulfils the first and the methodological objective of this thesis. It has explained in detail of the general structure of a standard CGE model and the development of the SEMM from sketch for this thesis specifically. The introduction to a standard CGE model has shown that CGE model is suitable for nexus assessment as it describes an economy as a whole and the linkages among its sectors. Furthermore, a CGE model has flexible structure to be linked with exogenously ecological models to capture nexus linkages outside of economic market.

So far no macroeconomic assessment has been made to explicitly analyse the impacts of OWFs expansion on seafood sectors from an energy-food nexus perspective. SEMM is therefore created to fill in this gap. One basic modelling framework and two additional modules are developed to concentrate on simultaneously capturing the relevant economic and environmental linkages that are affected by the expanding OWFs. The basic SEMM assesses the economic nexus linkages between the OWF electricity sector and the seafood sectors and the impacts of OWFs on energy security and fish supply from nexus perspective (Section 4.1). The innovative marine resource allocation module focuses on quantifying the spatial conflict between OWFs and fishing activities and therefore makes implications to marine spatial planning (Section 4.2).

The integrating natural capital and ecosystem services module extends the modelling framework to include the environmental impacts and nexus linkages between economy and environment (Section 4.3). The model results are supposed to assess the economic and environmental linkages between OWFs and seafood production, which can help maximize synergies and minimize trade-offs within the nexus framework.

Given the assumptions made to build the SEMM as discussed above, it should be careful when interpreting SEMM's results. It should be noted that as a comparative static model, the SEMM is not capable of providing short-term prediction, but rather concentrates on presenting the direction and relative magnitude of the adjustment of the economy after certain shocks (Thurlow, 2004). Therefore, the results presented below do not have implications on the time dimension nor on the real economic growth. The results highlight the different state of the economy after expansion in OWFs and show the nexus linkages between OWFs and seafood productions from the macroeconomic perspective.

4. Results

4.1. Application 1

The rapid expansion of OWFs in response to increasingly ambitious renewable energy targets has led to growing concerns about its overall socioeconomic impacts. As reviewed in Section 2.1.3 and 2.1.4, although there are impact assessments of expanding OWFs at the macroeconomic scale (e.g., GDP, employment), much less particular attention has been paid on assessing the detailed sectoral impacts and the subsequent knock-on effects on household behaviours.

The first application of the SEMM therefore tries to fill a gap in existing socioeconomic assessments by principally focusing on the sectoral impact of the expansion of OWFs on seafood production and on the associated household income, consumption and welfare effects across different household groups. It assesses the impacts of expanding OWFs on nexus linkages from (i) the indirect macroeconomic perspective (as mentioned in Section 1.1.4.1) by comparing the impacts of different OWF electricity costs; and (ii) from the direct environmental perspective (as mentioned in Section 1.1.4.2) by displaced fishing efforts. The SEMM results focus on how expansion of OWFs would change seafood and electricity availability (i.e., production), affordability and consequently distribution effects across household groups (i.e., consumption), and the macroeconomic impacts (i.e., GDP). Furthermore, sensitivity analysis regarding the substitution between the OWF electricity and the other electricity is conducted in this application, allowing changes in electricity inputs. These, in turn, generate a shift in technologies thereby producing the optimal electricity mix as a result of the impact of expanding OWFs.

4.1.1. Scenario simulations

The nexus implications of the expansion of OWFs are explored through a set of scenarios. Table 4.1 summarizes the three scenarios considered in this application.

Scenarios 1 and 2 compare the impacts of the recent OWF cost reduction on seafood sectors through the indirect macroeconomic nexus linkages and on the wider economy. The model is capable of capturing the economy-wide competition for capital and labour and the demand interactions implicit in each sector's supply chain. To better compare the impacts of different degrees of flexibility of capital use on model results, scenarios are simulated based on short-, long- and extra-long-run assumption. The primary motivation for presenting the three options is that capital is an important contributor to production, especially in the capital-intensive electricity sectors. Therefore restrictions in the flexibility of capital put constraints on the development of OWFs. It should be noted that the short- long- and extra-long-run do not refer to specific time dimension as each are imposed in a static CGE model; rather they compares different states of the economy regarding the flexibility of capital.

Table 4.1 Simulated OWFs production scenarios for Scotland in the SEMM for Application 1 (Source: BEIS, 2015, 2017, 2019; Scottish Government, 2018c)**.**

Model scenario	Impact assumptions	Shocks in model
Scenario 1	Second round of CfDs auction (AR2)	30% higher cost of OWFs sector and 35% subsidy on OWFs sector
Scenario 2	Third round of CfDs auction (AR3)	15% lower cost of OWFs
Scenario 3	Increasing fishing effort due to OWFs	10% decrease in productivity of fishing sector

The cost reduction in OWFs is attributed to technological improvements driven by public/private research and development (R&D), learning-by-doing, and economic scales (Carbon Trust, 2020). Such technological change is operationalised in the CGE model as a change in production efficiency in the OWF electricity sector (Lecca et al., 2017). It means that those drivers for OWF technology improvement are incorporated as an exogenous efficiency shock. The change in efficiency applies to all production inputs at the top level of the production nest: intermediate and factor inputs. It should be noted that the SEMM is static. This means that instead of applying the evolution of the technology improvement effects over time, the efficiency shock is applied as a permanent step change in order to compare the effects before and after the technology improvements.

The first two scenarios highlight and compare the expansion of OWFs under two contrasting situations. Scenario 1 introduces an exogenous 30% reduction in productivity in the OWF sector, which points to the situation reflected in the second round of CfD auctions (AR2) where the average strike price, £64/MWh, was 30% higher than the average wholesale price of electricity of £48.2/MWh. The CfD scheme subsidies the higher cost renewable energy to ensure the electricity generation moves towards a low-carbon future. In order to achieve the expansion in output a 35% subsidy is simultaneously imposed to cover the high cost of OWFs. This subsidy is introduced as a negative ad-valorem tax to the OWF sector. Scenario 1 therefore represents a subsidised expansion in OWFs where the sector is facing high costs with increased scale. This is a scenario which reflects the path to decarbonisation if this technologically is inherently increasingly costly and resource intensive.

In Scenario 2, the increased price competitiveness takes the form of a 15% improvement in OWF efficiency. This reflects the situation in the third round, AR3, of the auction of CfDs which registered a record-low average strike price of £41/MWh compared to the average wholesale electricity price of £48.2/MWh. Scenario 2 therefore shows the impact of an expansion in electricity generation powered by increasingly efficient renewables and reflects a more optimistic vision (i.e., efficient learning curve) for moving towards zero carbon.

The initial share of OWFs in the electricity generation is 10% and the default setting for the model assumes a fixed ratio between OWFs and other electricity generation in the domestic production of electricity to ensure the competitiveness of higher production cost OWFs, as required by government's renewable target. An alternative CES function is available for combining the OWF and other electricity sectors. With the CES function and an increase in OWF price competitiveness, expanding OWF production will not only increase the output of electricity as a whole, but also the share in electricity from OWFs. In this case, the elasticity between OWF and other electricity represents the sensitivity of the trade-off that the national grid is prepared to make across different generation types. For that reason, sensitivity analysis is conducted to test how sensitive the results in Scenario 1 and 2 are to variation in this elasticity value.

The aggregate effect of the direct impact on fishing activity from expanding OWFs is explored in Scenario 3. In this case fishing efficiency is assumed to fall due to a reduction in fishing opportunities (e.g. Alexander et al., 2013; Gray et al., 2016). In Scenario 3 this is simulated through the introduction of an exogenous 10% decrease in the productivity of all inputs in the fishing sector (Scottish Government, 2018b).

4.1.2. Results

4.1.2.1. Sectoral impacts on production activities and commodity sales

The percentage changes in the level and price of the eight sectoral production outputs (QA, PA) and the level and price of the seven domestic market commodities (QQ, PQ) are reported for all three scenarios in Table 4.2 and Table 4.3 respectively. Results for other important variables (i.e., value-added (QVA) and intermediate input used (QINTA), imports (QM) and exports (QE) and their prices) are shown as percentage changes in the Appendix (Table SI 4.1, Table SI 4.2).

Production activities

As Scenario 1 and 2 are comparative scenarios, their results are presented together below. The analysis of results starts with the electricity sectors, then the seafood sectors and finally the other sectors.

There are two general trends in the results of electricity sectors. First, note that in each simulation reported in Table 4.2, the proportionate changes in the domestic output for 'OWF electricity' and 'other electricity' sectors are exactly the same. This is because, as discussed in Section 3.2.1.2, the two electricity sectors are assumed to have a fixed share in the electricity generation mix. The limitation of the fixed share assumption and the sensitivity analysis regarding relaxing that assumption will be further discussed in Section 4.1.3. Second, as the capital constraint is released from the short- to the extra-long-run, the economic expansions in the electricity sectors are gradually enhanced.

In Scenario 1, the electricity sector' short-run outputs fall by -0.28% whilst the output price in both electricity sectors increases, but particularly in OWF where the rise is 9.66%. The reason is that subsidising the OWFs increases the capital demand in production. However, capital is fixed in the original sectors and cannot be substituted by labour in the model as capital and labour are complementary, so there is no capital to support expansion of OWFs. Therefore the OWF electricity output decreases but price increases. In Scenario 2, the short run shows the opposite results. Both electricity sectors experience a small (0.84%) output increase whereas the output price of OWF electricity shows a large (-15.54%) decrease. Although the constraint on sector-fixed capital still exists, the efficiency improvement requires less capital used in production so that the OWF electricity sector increases output. When the capital is flexible between sectors in the long-run, both electricity sectors expand, in the case of Scenario

2 to a larger extent. It should be noted that in the long-run, although the percentage increases in the domestic OWF electricity outputs are similar in both Scenario 1 (+5.33%) and Scenario 2 (+5.81%), the output price changes are quite different (-5.17% and -13.83% respectively). In Scenario 1 the positive impact of the subsidy outweighs the negative impact from the higher cost of OWFs that occurs in this scenario, so the reduction in output price is much lower than in Scenario 2. Furthermore, in the extra-long-run, the output expansion in both electricity sectors is even greater (+5.71% in Scenario 1 and +6.30% in Scenario 2) with even cheaper capital costs. The expansion in electricity sectors is enhanced as capacity constraints are removed, stimulating exports (Table SI 4.2), household consumption and investment (Table SI 4.3). Aggregate investment increases, adding to total capital stock, resulting in less significant impacts on the other sectors.

For the other sectors, the general trend is that the largest impacts occur in the long-run while the smallest impacts happen in the short run. Short-run changes in capital-intensive sectors (e.g., the fishing and the aquaculture sector as shown in Figure 3.3) tend to be in the same direction as changes in the electricity sectors reflecting constraint on capital. As labour is assumed to be mobile in the short-run, the relatively labour-intensive sectors (e.g., the agriculture, the fish processing, the industry and the service sectors as shown in Figure 3.3) tend to have changes that are the inverse of those in the electricity sectors, mostly influenced by the mobile labour. The reasons for the labour movement are the same in both scenarios, which is correlated to the output variations in the other electricity sector. Labour intensive sectors increase outputs benefited from less demand in labour when there is reduced production outputs of the other electricity sector in Scenario 1 and decrease outputs because the other electricity sector need more labour to increase production in Scenario 2. As mentioned earlier in Section 3.2.1.2, such free mobile labour is possible based on marginal adjustments to the distribution of the labour force across sectors, which is supported by the fact that fishermen could apply their knowledge and skills of the fishing industry on expanding renewable energy sector (Austin et al., 2002; Perry et al., 2012).

Table 4.2 Percentage changes (%) in production activity for different sectors

	Scenario 1			Scenario 2			Scenario 3		
Variable	Short-run	Long-run	Extra-long run	Short-run	Long-run	Extra-long run	Short-run	Long-run	Extra-long run
Production Activity	*Production Sector Output (QA)*								
Agriculture	0.01	-0.36	-0.03	0.00	-0.71	-0.21	0.00	-0.02	-0.08
Fishing	-0.02	-2.75	-0.80	0.00	-3.36	-0.91	-1.09	-13.49	-13.70
Fish processing	0.05	-1.41	-0.76	-0.04	-1.86	-1.05	-0.06	-4.24	-4.32
Aquaculture	-0.02	-5.49	0.04	0.01	-5.11	2.06	0.00	-1.49	-2.23
Other electricity	-0.28	5.33	5.71	0.84	5.81	6.30	0.00	0.06	0.01
OWF electricity	-0.28	5.33	5.71	0.84	5.81	6.30	0.00	0.06	0.01
Industry	0.03	0.33	0.30	-0.01	-0.11	-0.05	0.00	0.07	0.07
Services	-0.04	-0.25	-0.19	0.00	-0.06	-0.02	0.00	0.02	0.01
	Price of Domestic Output (PA)								
Agriculture	0.05	0.12	0.01	-0.02	0.15	0.01	0.00	-0.02	0.00
Fishing	0.06	0.06	0.02	-0.02	0.05	0.04	0.05	0.58	0.59
Fish processing	0.05	0.03	0.00	-0.02	0.03	0.00	0.00	0.17	0.17
Aquaculture	0.06	0.10	-0.04	-0.02	0.07	-0.11	0.00	-0.03	-0.01
Other electricity	0.25	-0.22	-0.32	1.17	-0.75	-0.88	0.00	-0.02	0.00
OWF electricity	9.66	-5.17	-5.21	-15.54	-13.83	-13.88	0.00	-0.01	0.00
Industry	0.09	-0.01	0.00	-0.02	-0.01	0.01	0.0	0.0	0.00
Services	-0.05	0.02	0.02	0.02	0.05	0.05	0.0	0.0	0.00

In the long-run, where electricity production expands, many elements of the economy, apart from industry, are negatively impacted. Rising demand from expanding OWFs triggers net transfer of labour and capital from other sectors. This includes the seafood sectors. As argued earlier, being smaller sectors they are likely to have more idiosyncratic cost structures. This implies that these sectors are more likely to deviate from the average reaction to exogenous shocks and are more sensitive to movements in the prices of production inputs. Among the three seafood sectors, the reason why the fishing and aquaculture sectors are most strongly affected is primarily the same as for the short-run results; these sectors are relatively capital-intensive. The flexible mobile capital between OWFs and seafood sectors could be interpreted from empirical perspective that fishing vessels could be used to provide support services or surveying for OWF projects (Blyth-Skyrme, 2010). The fish processing sector suffers some knock-on effects from reductions in the capture and aquaculture fish supplies as intermediate inputs. Also as a result of inter-sectoral movement in capital and labour, production in the aggregated agriculture and services sectors falls. Being an important input for electricity production, the output of the industry sector increases slightly in Scenario 1 but decreases in Scenario 2, because of higher production efficiency of electricity in Scenario 2.

In the extra-long run, without the constraint of a fixed aggregate capital stock, the negative impacts of expanding OWFs on other sectors become less significant than in the long-run results. It is particularly obvious for capital-intensive sectors; the fishing sector has lower reduction in output and the aquaculture sector even has a small increase in output when capital stock increases as a result of expansion in OWFs. It is less obvious for labour-intensive sectors like agriculture, fish processing and industry and service sectors where labour is a more pressing constraint on production.

As for Scenario 3, the reduced productivity in the fishing sector has negative impacts, particularly on the seafood sectors. Directly affected by reduced productivity, the output of the fishing sector falls with a small increase in price. Outputs in the fish processing sector also decrease mainly due to a reduction in fish to be used as a main production input. The same reason explains the output reduction in agriculture and aquaculture but to a lesser extent as they need less fish as inputs. Similar to the other two scenarios, such negative impacts are minor in the short run and largest in the extra-long run. Unlike Scenarios 1 and 2 where an expansion in OWFs would induce an increase in the aggregate demand for capital, less efficient fishing activities reduces capital demand. In the extra-long run, capital rentals fall so that capital supply is reduced, and has its most significant impacts. The non-food sectors experience no change in the short run, due to fixed capital constraint. They have minor output increases in the long-run, benefiting from capital released from the small seafood sectors, whereas such increase becomes less significant as total capital stock falls in the extra-long run.

Commodity sales

It can be seen that most commodity sales generally follow the same trend as production activities under short-run, long-run and extra-long-run across three scenarios, except for electricity (Table 4.3). The reason is the relatively large amount of electricity that is used in the production of electricity (e.g., conversion losses and distribution losses as mentioned in Section 3.2.1.1). In Scenario 1, OWF production is expanding together with a reduction in the efficiency with which it is produced: this implies that the electricity input per unit of output of OWF increases. However, in Scenario 2 the input of electricity per unit of OWF falls and thus less electricity needed as the intermediate input. This difference in the demand for electricity as an intermediate input accounts for the counterintuitive electricity sales results. Therefore, in the short run, electricity commodity sales increase whilst the electricity production sectors' outputs fall in Scenario 1 whereas the opposite happens in Scenario 2. It also explains why the increase in electricity commodity sales is greater in Scenario 1 than in Scenario 2.

Table 4.3 Percentage changes (%) in commodity sales for different sectors

Variable	Scenario 1			Scenario 2			Scenario 3		
	Short -run	Long -run	Extra -long run	Short -run	Long -run	Extra -long run	Short -run	Long -run	Extra -long run
Commodity sales	*Domestic market commodity sales (QQ)*								
Agriculture	0.02	0.02	0.11	0.01	-0.16	-0.05	0.00	-0.11	-0.12
Fishing	-0.02	-1.31	-0.71	0.03	-1.68	-0.92	-0.06	-3.87	-3.95
Fish processing	0.14	-0.35	-0.20	-0.04	-0.24	-0.06	-0.01	-0.63	-0.65
Aquaculture	-0.07	-3.35	0.30	0.01	-3.23	0.72	-0.02	-2.33	-2.74
Electricity	1.76	3.98	4.17	-0.06	1.83	2.07	0.00	0.01	-0.02
Industry	0.18	0.33	0.43	-0.03	0.01	0.13	0.00	-0.01	-0.03
Services	0.19	-0.21	-0.14	0.06	0.05	0.14	0.00	0.00	-0.01
	Price of domestic market commodity (PQ)								
Agriculture	0.05	0.11	0.00	-0.02	0.15	0.01	0.00	-0.01	0.00
Fishing	0.07	0.22	-0.01	-0.02	0.24	-0.05	0.17	1.67	1.70
Fish processing	0.04	0.07	0.03	-0.01	0.10	0.04	0.00	0.32	0.32
Aquaculture	0.05	0.30	-0.07	-0.02	0.24	-0.23	0.00	-0.11	-0.06
Electricity	1.18	-0.72	-0.82	-0.51	-2.10	-2.23	0.00	-0.01	0.00
Industry	0.09	-0.01	0.01	-0.02	-0.01	0.02	0.00	-0.01	-0.01
Services	-0.06	0.02	0.02	0.02	0.06	0.06	0.00	0.00	0.00

For seafood sectors, sales also follow a similar trend but tend to change less than the outputs. In most cases, the decline in the domestic production of seafood is negatively impacted by expanding OWFs and seafood becomes more expensive, which results in reduced demand, both in domestic (Table 4.3) and export markets (Table SI 4.2).

Therefore their commodity sales decrease with slightly higher sales prices. When there are increases in production outputs, such as the short-run case in Scenario 2 and the extra-long-run case in both scenarios, there are also minor corresponding increases in commodity sales. For the remaining sectors, the sectoral domestic production directly impacts the corresponding commodity sales and prices.

4.1.2.2. Changes in household income and welfare distribution

Table 4.4 shows the percentage changes in household income across household groups. In all scenarios the impact on incomes across all households is small.

In the short run, in both scenarios, as OWFs expand, households have slight income increases as they benefit from the significant increased capital rental income, mainly from electricity sectors. Under the long-run assumption, as OWFs expand, other sectors are forced to release both capital and labour. Because the electricity sectors are relatively capital intensive, the economy-wide capital rental rate rises and the wage falls. Household incomes depend more heavily on wage payments so all households show slightly reduced incomes. The increasingly inefficient OWFs expansion, as outlined in Scenario 1, results in slightly larger negative changes household incomes. When capital is no longer constraint in the extra-long run, labour is still under fixed supply so that increasing demand for labour results in slightly increase in household income. Moreover, the incomes of lower-income households vary less than those of higher-income households, whose incomes rely more heavily on wages and capital rental (Figure 3.5). The change is similar in Scenario 3 but the variations in wage and capital rentals are so small that there are only minor impacts on household incomes.

Table 4.4 Percentage change (%) in household income

	Scenario 1			Scenario 2			Scenario 3		
Variable	Short run	Long run	Extra-long run	Short run	Long run	Extra-long run	Short run	Long run	Extra-long run
Household income									
HH1	0.01	-0.01	0.01	0.01	0.00	0.02	0.00	0.00	0.00
HH2	0.01	-0.03	0.02	0.01	-0.02	0.05	0.00	0.01	0.00
HH3	0.01	-0.05	0.03	0.01	-0.04	0.06	0.00	0.01	0.00
HH4	0.01	-0.07	0.04	0.02	-0.05	0.08	0.00	0.01	0.00
HH5	0.02	-0.05	0.05	0.03	-0.03	0.10	0.00	0.01	0.00

The household welfare is valued by the equivalent variation measure (EV) (Figure 4.1). The first finding is that welfare for all household quintiles falls in Scenario 1, increases in Scenario 2, and almost no change in Scenario 3. The reason for welfare loss in Scenario 1 is the more expensive electricity in the short run, the income reduction in the long run, and the decreasing consumption on other commodities in the extra-long run. It can be seen that increases in the electricity price in the short run has the most negative impact on household welfare, given that electricity is a necessity for all households. This reduced welfare is expected given that Scenario 1 is forcing the expansion of the OWF electricity sector whist simultaneously reducing its efficiency.

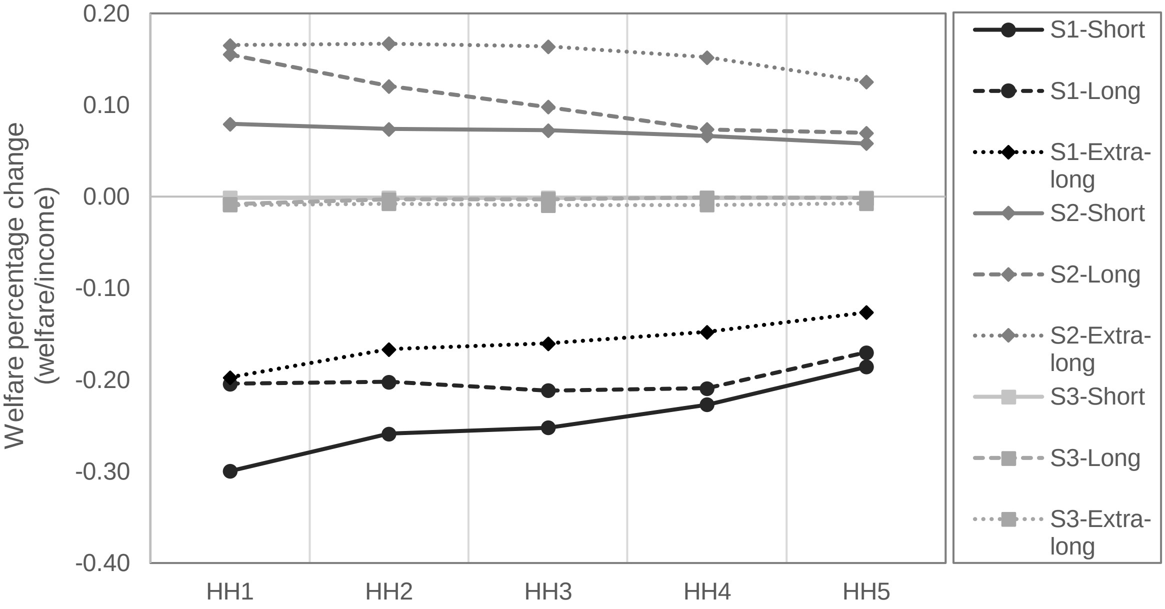


Figure 4.1 Changes in equivalent variation divided by household income (%) by household quintiles with solid line represent short-run and dash line represent long-run.

In Scenario 2 all households experience a welfare improvement with lower income households consistently benefiting the most. Such welfare gain is again related to the electricity price; household welfare increases least in the short run when the fall in the electricity price is the lowest whereas it increases the most in the extra-long run, where the electricity price experiences the largest fall. Another important finding is that the lower the income a household has, the greater the welfare increases. It shows that lower income households have relatively less disposable income to spend and thus are more sensitive the key to economic change which is the variation in electricity price due to OWF expansion in these two scenarios. Decreased fishing productivity in

Scenario 3 again has only slight impacts on households, as fishing is a small sector in the economy.

4.1.2.3. Macroeconomic impacts

For all simulations, the proportionate changes in GDP are given in Figure 4.2. The macroeconomic results show that the expansion in OWF output accompanied by a reduction in OWF efficiency, as in Scenario 1, has an overall negative impact on GDP (-0.22%, -0.21%, -0.14% for the short-, long- and extra-long-runs respectively). In contrast, the increased efficiency of electricity from OWFs in Scenario 2 produces a small increase in GDP of 0.06% in the short run, 0.08% in the long-run, and 0.16% in the extra-long run. In Scenario 3, reducing productivity in the fishing sector has a negligible impact on the economy at a macro scale.

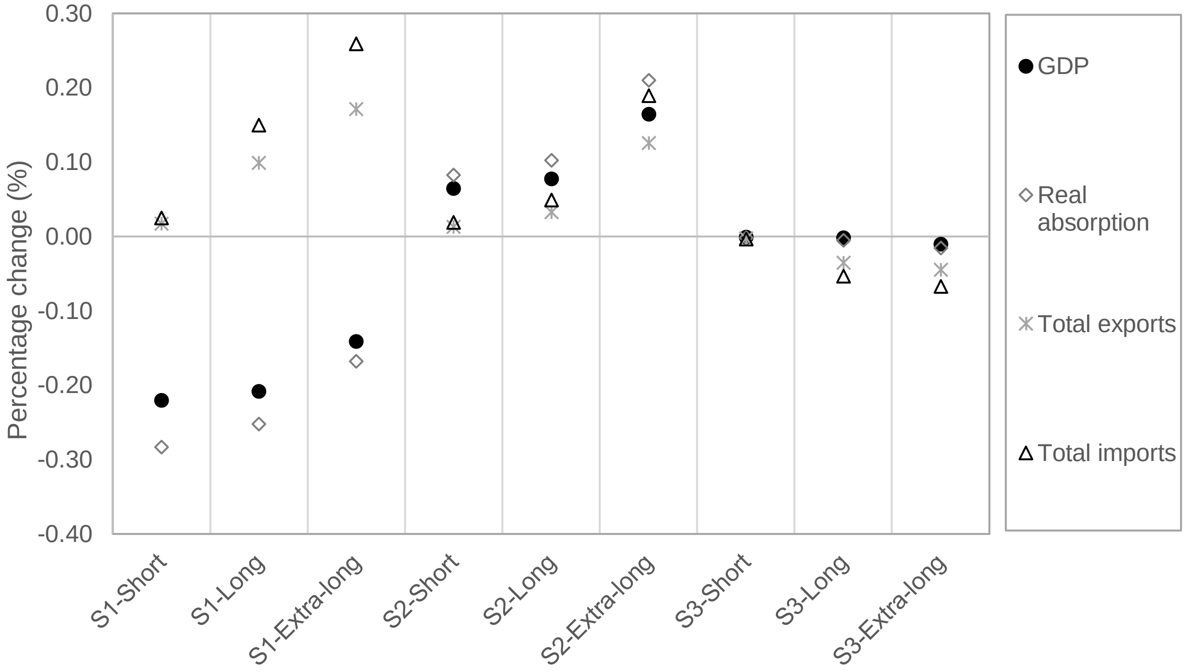


Figure 4.2 Percentage changes (%) in macroeconomic variables in different scenarios simulated

GDP equals real absorption plus the trade balance (total exports – total imports). Real absorption is defined as the sum of private consumption, government spending and gross investment (results shown in Supplementary Table SI 4.3). The proportionate change in GDP is the weighted sum of the proportionate changes in real absorption and the trade balance. In first two scenarios, the proportionate change in the real absorption dominates in determining the change in GDP. In Scenario 1, the proportionate change in GDP is heavily influenced by the negative change in real absorption arising from decreased household consumption due to more expensive electricity in the short run, less household income in the long run, and more expensive other commodities in the extra-long run. In contrast, in Scenario 2 GDP increases as cheaper electricity causes real absorption to increase significantly to cover the trade deficit. This finding can also be shown from the trend that GDP increases are correlated with cheaper electricity from the short run to the extra-long run. There is no significant change in Scenario 3. In the long-run, the total exports decrease slightly reflecting the falling domestic production of seafood whereas the total imports also fall slightly due to reduced demand. The decline in total exports and total imports balance the trade deficit, together with no significant change in real absorption, resulting in no change in GDP.

4.1.3. Sensitivity analysis

The sensitivity analysis maps the reaction of sectoral output values to variations in the elasticity of substitution (σ_a^{el}) between the two electricity production sectors in the generation of the composite electricity commodity. This elasticity reflects the degree to which a low-carbon offshore wind generation technology is substitutable for other electricity generation, which relates to the evolution of technical change between OWFs and fossil fuels (Acemoglu et al., 2012). At present OWFs are not perfect substitutes for non-intermittent fossil fuels as an intermittency energy source due to limited technology of storability and transmission to the national grid (Madrigal and Stoft, 2012).

Increasing the substitution elasticity where the price of OWF output is falling has two effects. First, it increases the output of the OWF sector, as OWF electricity is substituted for other electricity output. Second, the impacts of OWFs on the electricity commodity price will increase as the importance of the OWF sector in the electricity commodity composite rises. The absolute size of the negative impacts on seafood sectors would also be reduced in line with the falling price of electricity. To test this, the elasticity (σ_a^{el}) is increased under Scenarios 1 and 2. Results for the default fixed share ($\sigma_a^{el} = 0$) are compared to those where there is some flexibility, with the two sectors as complements ($\sigma_a^{el} = 0.5$) and low substitutes ($\sigma_a^{el} = 1.5$). The simulations are also instructive in that they identify the ease with which the share of OWFs in total electricity generation could be increased. These results are shown in Table 4.5.

Table 4.5 The sensitivity of selected sectoral outputs to alternative values of the elasticity $\boldsymbol{\sigma_a^{el}}$ (% change in sectoral output of seafood production and electricity generation sectors)

Production sectors	Default (Fixed share)			Complementary ($\sigma_a^{el} = 0.5$)			Substitutable ($\sigma_a^{el} = 1.5$)		
	Short-run	Long-run	Extra-long-run	Short-run	Long-run	Extra-long-run	Short-run	Long-run	Extra-long-run
				Scenario 1					
Fishing	-0.02	-2.75	-0.80	-0.03	-2.04	-0.35	-0.03	-1.99	-0.39
Fish processing	0.05	-1.41	-0.76	0.03	-1.01	-0.42	0.03	-1.01	-0.46
Aquaculture	-0.02	-5.49	0.04	-0.04	-4.02	0.77	-0.05	-3.78	0.73
Other electricity	-0.28	5.34	5.71	0.01	4.37	4.59	0.14	4.08	4.28
Offshore wind electricity	-0.28	5.34	5.71	-3.27	7.05	7.25	-6.57	12.31	12.45
Share of offshore wind	10	10	10	9.72	10.24	10.24	9.41	10.72	10.73
				Scenario 2					
Fishing	0.00	-3.36	-0.91	-0.01	-1.18	-0.39	-0.02	-0.86	-0.34
Fish processing	-0.04	-1.86	-1.05	-0.04	-0.63	-0.08	-0.05	-0.56	-0.14
Aquaculture	0.01	-5.11	2.06	0.03	-0.39	4.33	0.04	0.85	4.50
Other electricity	0.84	5.81	6.30	0.65	2.85	3.05	0.41	1.7	1.85
Offshore wind electricity	0.84	5.81	6.30	9.11	10.37	10.55	21.96	25.66	25.78
Share of offshore wind	10	10	10	10.76	10.67	10.68	11.91	12.09	12.10

As the elasticity of substitution between electricity sectors increases, the changes in output of the OWF sector becomes more significant and the impact on the other electricity sector is reduced. This reflects the extent to which the OWF electricity sector replaces or is replaced by the other electricity sector. When OWF electricity becomes expensive in the short run in Scenario 1, the high cost of OWFs under the capital constraint leads to a greater decrease in OWF electricity outputs which are replaced by relatively cheaper other electricity as they become closer substitutes. This leads to a corresponding lower share of OWF in total electricity to 9.72% and 9.41% respectively as the elasticity of substitution is increase. This relates back to the reason for choosing the fixed share between OWF and other electricity as default setting because the government has certain renewable energy target to reach (Scottish Government, 2019g). The fixed share assumption guarantees that OWFs would not be replaced by other electricity in this case. When the OWF electricity becomes cheaper in the long-run and extra-long run, the OWF sector produces more output, replaces other electricity and increases its share in total electricity generation. This also applies to Scenario 2, where OWF is capable of increasing its share in total electricity generation. The OWF price is lower in Scenario 2 due to cost reduction powered by the increase in efficiency. This allows OWF to increase its share in total electricity generation to a greater extent than in Scenario 1 as it becomes a more price competitive energy source.

Increasing the substitution elasticity limits the proportionate reduction in the output of the fishing and fish processing sectors, but the variation is relatively small. For aquaculture the same pattern emerges but the effect of varying the elasticity is greater. This is especially the case in Scenario 2 long-run result, where the sector contracts by 5.11% with the default value but increases by 0.85% when the two electricity generating sectors are substitutes. It is expected that being a luxury good, aquaculture is sensitive to price change so that aquaculture could benefit from the lower electricity price in Scenario 2.

It can be concluded from the sensitivity analysis that: with increasing elasticity of substitution between OWF and other electricity, the direction of impacts of OWF expansion on seafood sectors is consistently negative (except the aquaculture sector), whereas the magnitude of such impacts becomes less significant. However, whether the OWF electricity could be highly substitutable with other electricity is still in doubt since OWFs are an intermittent electricity source (Timilsina et al., 2012). Essentially what is being tested is the robustness of the model results. Therefore, the sensitivity analysis demonstrates the negative impact of OWF expansion on seafood sectors through the indirect macroeconomic nexus linkages. Assessing such nexus linkages between OWFs and seafood sectors is not intended to make predictions on the outcome of future scenarios, but rather serve to illustrate how the Scottish economy adjusts to the OWF expansion shocks affecting key components of seafood production. Therefore, identifying, quantifying and managing the nexus between offshore wind energy and seafood supply will be of great importance in achieving the GHG target without jeopardising other economic and social goals.

4.1.4. Conclusion

With fast development and rapidly falling costs, OWFs are likely to play an important role in increasing energy security and reaching the net-zero emission target of the UK Government. In particular, the recently announced record-low strike price of OWFs from AR3 will encourage further deployment of OWFs. However, expanding OWFs may bring conflicts with seafood supply because of indirect impacts through macroeconomic linkages and direct impacts through displacing fishing effort, which are described in the energy-food nexus approach in this thesis. Hence, the SEMM is firstly applied to analyse, through the nexus linkages, the potential impacts on seafood production of expanding OWFs under a cost reducing trend. The corresponding impacts on the wider economy are also simulated.

This first application of SEMM suggests that the economy overall would be negatively impacted by OWFs when the cost of OWFs is higher than the wholesale electricity price, but would benefit from OWFs when their cost is lower. At aggregate level, the impacts of OWFs on the economy would become less significant with increasing flexibility of capital (from sector-constrained capital to flexible capital stock). At the sectoral level, the OWF sector tends to expand to a larger extent with sufficient capital used in production. For other sectors, the impacts of OWFs on their production are the least significant in the short run due to the sectoral capital constraint, and are the most significant in the long run as OWF bids away the limited capital.

From the energy-food nexus perspective, energy security would not be enhanced by high-cost OWFs (Scenario 1), especially in the short run when electricity production decreases with higher prices. Although the CfD scheme could stimulate the production of OWFs, under these circumstances households would not benefit. Only low-cost OWFs (Scenario 2) would benefit energy security by both expanding production and making electricity cheaper for households, thereby providing welfare benefits. Production in seafood sectors is reduced through the macroeconomic linkages as an expansion in the output of the OWF sector creates negative impacts by bidding away production factors. The direct impacts through displacement of the fishing effort (Scenario 3) are confined to the three seafood sectors, with negligible impacts on the rest of economy as the affected sectors are small. As for the distributional effects on household groups, lower income households are sensitive to electricity price changes as electricity is an essential commodity for households. This suggests that low-cost OWFs would help mitigate fuel poverty, especially for the lowest-income households.

A CGE modelling framework is a powerful assessment tool for energy-food nexus analysis, but this first application still suffers from a limitation on nexus assessment. The simulation results have focused primarily on the production and consumption interaction between OWFs and seafood from the macroeconomic perspective. Note that the model identifies only the competition between energy and seafood sectors for economy-wide factors of production, labour and capital. In the approach adopted here no direct systematic links are specified as the result of the competitive use of scarce marine resources such as the replacement of fishing grounds with OWF areas. Therefore, an improved model structure to allow competition and reallocation of marine areas is introduced in the next application of the SEMM model, which could provide a stronger direct link between OWFs and seafood productions in the nexus approach.

4.1.5. Supplementary Information

Table SI 4.1 Percentage changes (%) in production activity inputs and their prices

Variable	Scenario 1			Scenario 2			Scenario 3		
	Short run	Long run	Extra-long run	Short run	Long run	Extra-long run	Short run	Long run	Extra-long run
				Production factor (QVA)					
Agriculture	0.00	-0.38	0.03	0.00	-0.73	-0.22	0.00	-0.02	-0.08
Fishing	0.00	-2.78	-0.80	0.00	-3.41	-0.93	-1.10	-13.60	-13.81
Fish processing	0.06	-1.38	-0.77	-0.04	-1.84	-1.08	-0.04	-4.19	-4.27
Aquaculture	0.00	-5.51	0.02	0.00	-5.15	2.02	0.00	-1.49	-2.23
Other electricity	-0.05	5.22	5.60	0.31	5.50	6.00	0.00	0.06	0.01
OWF electricity	16.93	50.31	50.84	-7.36	-8.28	-7.85	0.00	0.06	0.01
Industry	0.04	0.32	0.29	-0.02	-0.13	-0.17	0.00	0.07	0.07
Services	-0.03	-0.26	-0.19	0.00	-0.07	0.01	0.00	0.02	0.01
				Production factor (PVA)					
Agriculture	0.06	0.17	0.01	-0.02	0.22	0.03	0.00	-0.02	0.00
Fishing	0.01	0.15	0.01	0.00	0.21	0.03	0.09	0.99	1.01
Fish processing	0.05	-0.06	0.04	-0.01	-0.03	0.10	-0.03	0.01	0.00

Aquaculture	-0.01	0.16	0.01	0.01	0.22	0.03	0.00	-0.02	0.00
Other electricity	-0.50	0.15	0.01	2.96	0.21	0.03	0.00	-0.02	0.00
OWF electricity	121.17	0.06	0.02	-18.98	0.11	0.06	0.00	-0.01	0.00
Industry	0.07	0.00	0.03	-0.01	0.05	0.08	0.00	0.00	0.00
Services	-0.07	0.03	0.03	0.03	0.07	0.07	0.00	0.00	0.00
Intermediate input (QINT)									
Agriculture	0.01	-0.34	0.04	0.00	-0.67	-0.20	0.00	-0.03	-0.08
Fishing	-0.04	-2.72	-0.78	0.01	-3.30	-0.88	-1.07	-13.34	-13.54
Fish processing	0.05	-1.42	-0.75	-0.04	-1.87	-1.03	-0.06	-4.27	-4.34
Aquaculture	-0.04	-5.48	0.05	0.02	-5.07	2.10	0.00	-1.48	-2.23
Other electricity	-0.48	5.44	5.80	1.32	6.08	6.56	0.00	0.06	0.01
OWF electricity	48.45	50.50	51.04	-13.01	-7.95	-7.52	0.00	0.06	0.01
Industry	0.03	0.34	0.31	-0.01	-0.08	-0.12	0.00	0.07	0.07
Services	-0.05	-0.25	-0.18	0.01	-0.05	0.03	0.00	0.02	0.01
Intermediate input price (PINT)									
Agriculture	0.04	0.03	0.00	-0.01	0.03	-0.01	0.00	-0.01	0.00
Fishing	0.14	-0.06	-0.06	-0.05	-0.16	-0.16	0.00	-0.01	-0.01
Fish processing	0.06	0.08	-0.02	-0.02	0.07	-0.06	0.02	0.26	0.27
Aquaculture	0.12	0.05	-0.08	-0.05	-0.07	-0.24	0.00	-0.04	-0.02
Other electricity	0.90	-0.54	-0.61	-0.38	-1.58	-1.67	0.00	-0.01	0.00
OWF electricity	0.63	-0.37	-0.41	-0.26	-1.06	-1.12	0.00	-0.01	0.00
Industry	0.10	-0.04	-0.03	-0.04	-0.10	-0.10	0.00	-0.01	-0.01
Services	0.00	0.00	0.00	0.00	-0.01	-0.01	0.00	0.00	0.00

Table SI 4.2 Percentage changes (%) in foreign exchange rate, exports, and imports

	Scenario 1			Scenario 2			Scenario 3		
Variable	Short run	Long run	Extra-long run	Short run	Long run	Extra-long run	Short run	Long run	Extra-long run
EXR	0.06	-0.01	-0.02	-0.02	-0.04	-0.04	0.00	0.01	0.01
Exports (QE)									
Agriculture	0.02	-0.63	-0.02	-0.01	-1.09	-0.32	0.00	0.03	-0.05
Fishing	-0.02	-2.79	-0.80	0.01	-3.41	-0.91	-1.12	-13.74	-13.95
Fish processing	0.06	-1.43	-0.77	-0.04	-1.89	-1.07	-0.06	-4.31	-4.39
Aquaculture	-0.02	-5.55	0.04	0.01	-5.16	2.09	0.00	-1.47	-2.22
Electricity	-2.49	6.83	7.40	1.83	10.22	10.99	0.00	0.11	0.05
Industry	-0.02	0.33	0.25	-0.01	-0.15	-0.25	0.00	0.10	0.11
Services	0.19	-0.32	-0.27	-0.07	-0.23	-0.17	0.00	0.05	0.04
Imports (QM)									
Agriculture	-0.03	0.27	0.15	0.02	0.20	0.06	0.00	-0.16	-0.15
Fishing	0.03	-0.85	-0.68	-0.03	-1.14	-0.93	0.27	-0.66	-0.68
Fish processing	-0.18	-0.17	-0.11	0.05	0.04	0.11	0.00	-0.02	-0.03

Aquaculture	-0.08	-2.74	-0.40	0.02	-2.69	0.34	-0.03	-2.57	-2.88
Electricity	4.06	2.51	2.51	-1.03	-2.34	-2.35	0.00	-0.05	-0.05
Industry	0.25	0.33	0.49	-0.04	0.07	0.27	0.00	-0.05	-0.07
Services	-0.43	-0.14	-0.05	0.14	0.24	0.35	0.00	-0.03	-0.05

Table SI 4.3 Percentage changes (%) in household consumption and government consumption (real absorption)

Variable	Scenario 1			Scenario 2			Scenario 3		
	Short run	Long run	Extra-long run	Short run	Long run	Extra-long run	Short run	Long run	Extra-long run
Household consumption									
Agriculture	-0.11	-0.09	-0.07	0.03	0.03	0.07	0.00	0.00	0.00
Fishing	-0.24	-0.23	-0.14	0.07	0.05	0.16	-0.03	-0.31	-0.32
Fish processing	-0.24	-0.20	-0.15	0.07	0.08	0.14	0.00	-0.06	-0.07
Aquaculture	-0.59	-0.62	-0.32	0.18	0.11	0.49	0.00	0.05	0.01
Electricity	-0.39	-0.07	-0.02	0.14	0.41	0.47	0.00	0.00	-0.01
Industry	-0.60	-0.45	-0.35	0.17	0.23	0.35	0.00	0.00	-0.02
Services	-0.53	-0.48	-0.36	0.16	0.20	0.34	0.00	-0.01	-0.02
Government consumption (QG)									
Agriculture	-0.05	-0.11	0.00	0.02	-0.15	-0.01	0.00	0.01	0.00
Fishing	-0.07	-0.22	0.01	0.02	-0.24	0.05	-0.17	-1.64	-1.67
Fish processing	-0.04	-0.07	-0.03	0.01	-0.10	-0.04	0.00	-0.32	-0.32
Aquaculture	-0.05	-0.30	0.07	0.02	-0.24	0.23	0.00	0.11	0.06
Electricity	-1.17	0.73	0.83	0.51	2.15	2.28	0.00	0.01	0.00
Industry	-0.09	0.01	-0.01	0.02	0.01	-0.02	0.00	0.01	0.01
Services	0.06	-0.02	-0.02	-0.02	-0.06	-0.06	0.00	0.00	0.00
Investment (QINV)									
Agriculture	0.00	0.00	0.17	0.00	0.00	0.21	0.00	0.00	-0.02
Fishing	0.00	0.00	0.17	0.00	0.00	0.21	0.00	0.00	-0.02
Fish processing	0.00	0.00	0.17	0.00	0.00	0.21	0.00	0.00	-0.02
Aquaculture	0.00	0.00	0.17	0.00	0.00	0.21	0.00	0.00	-0.02
Electricity	0.00	0.00	0.17	0.00	0.00	0.21	0.00	0.00	-0.02
Industry	0.00	0.00	0.17	0.00	0.00	0.21	0.00	0.00	-0.02
Services	0.00	0.00	0.17	0.00	0.00	0.21	0.00	0.00	-0.02

4.2. Application 2

With the growth of offshore renewable energy, there is reduced access to traditional fishing grounds, leading potentially to decreased landings. As reviewed in Section 2.1.1, areas enclosed by OWFs may replace the existing fishing grounds as fishermen are either forbidden from fishing due to safety exclusion zones or reluctant to operate within these areas. These negative impacts on fisheries have the potential to change fish catches and the market availability of fish, which could eventually reduce the food supply from the marine environment. Although the potential physical impacts of OWFs on fishing activity have been recognised, there is only limited quantitative work that evaluates the trade-offs between them (e.g. Lester et al., 2013; White et al., 2012; Yates et al., 2015). Furthermore, little is known about the wider economic effects of such replacement (de Groot et al., 2014; Lester et al., 2013; Punt et al., 2009).

This application therefore aims to quantify the macroeconomic impacts of spatial conflict between expanding OWFs and the fishing sector by introducing a new production factor called marine resource representing marine areas into the SEMM (as described in Section 3.2.2). The analysis first compares the model results with and without the marine resource allocation module to highlight the importance of incorporating direct spatial conflict into the nexus assessment. Furthermore, this application tests the impact of differences in the efficiency in the use of marine resource between OWFs and fishing activity. This could be applicable to MSP by presenting quantitative results of how increased efficiency through more effective marine planning can reduce significant negative impacts on seafood production of expanding OWFs.

4.2.1. Scenario simulations

Four scenarios have been constructed to compare the different marine resource replacement impacts as OWF development increases (Table 4.6). The Scottish Government has consented 4.1 GW of OWF projects, which is equivalent to a 348% increase on current capacity (981 MW) (Scottish Government, 2019b). It is assumed in the model that this same 348% increase in OWFs production occurs across all scenarios. To achieve the target of such a significant expansion in OWFs, the Scottish Government would need to subsidise the OWF electricity sector with various alternatives concerning different scenarios. In each simulation the government subsidy is just sufficient to achieve the required output expansion. Furthermore, such a significant expansion in OWFs is not achievable under the short-run sector-fixed capital assumption, all simulations are run under the long-run assumption of freely mobile capital between sectors.

Table 4.6 Simulated marine resource replacement scenarios for Scotland in the SEMM for Application 2. The subsidy rate applied has various alternatives to guarantee the same 348% increase in OWF electricity production output concerning different conditions in four scenarios.

Scenario	Assumptions made	Marine resource replacement	Production efficiency	Shocks in the model
Baseline scenario (S0)	Only macroeconomic linkages	No	No	$ta_a = -0.53$
Marine resource trade-off scenario (S1)	Accounting for marine spatial conflict	Yes	No	$ta_a = -0.53$
Low efficiency scenario (S2)	No marine spatial plan	Yes	20% lower	$ta_a = -0.55$ $\alpha_a^{va} = \alpha_a^{va} \times 0.8$
High efficiency scenario (S3)	Applied marine spatial plan	Yes	20% higher	$ta_a = -0.52$ $\alpha_a^{va} = \alpha_a^{va} \times 1.2$

Note: ta_a is the ad-valorem tax to production sectors, where the subscript a is the OWF sector and the negative tax represents subsidy. α_a^{va} is the shift parameter in the CES function and the superscript va represents the function is applied to the value-added level where the inputs are the marine resource and capital-labour composite.

Given this 348% increase, model simulations are used to assess different levels of reallocation of marine resource as fishing grounds are converted to OWF areas. The baseline scenario (S0) assumes the expansion impacts purely through macroeconomic linkages as a reference scenario, using the basic SEMM structure without the marine resource allocation module. The marine resource trade-off scenario (S1) introduces a fixed marine resource that is allocated between the OWF and fishing sectors. These two scenarios compare the differences in the outcomes with and without competition for marine resource in the CGE model. To show how the marine spatial plan may impact the outputs of marine activities, low and high efficiency scenarios (S2 and S3) for marine resource use have been run. The low marine resource use efficiency scenario (S2) refers to poorly specified or implemented marine spatial planning and/or lack of technology development, by assuming 20% lower efficiency. The high marine resource use efficiency scenario (S3) assumes that better marine spatial planning and technology development may mitigate trade-offs between competitive marine activities, assuming 20% higher efficiency. The change in efficiency is applied in the model by adjusting the shift parameter in the OWF electricity production function.

4.2.2. Results

4.2.2.1. Changes in marine resource

The changes in the marine resource under different scenarios are summarised in Table 4.7. As the marine resource is allocated in a fully competitive manner between the OWF electricity and fishing sectors, the expansion of OWFs would reallocate some of the marine resource from the fishing sector towards the OWF electricity sector so the share of fishing sector in total marine resource would fall and the OWF electricity sector correspondingly rise. No marine resource constraint is imposed in the baseline scenario, S0. However, in S1, as the expansion of OWF electricity production increases its demand for factor inputs, the marine resource available to the fishing sector decreases. Compared to this basic trade-off scenario S1, in the low efficiency scenario, S2, the OWF electricity sector needs more marine resource to produce same amount of output, whereas it demands less marine resource in the high efficiency scenario S3. In the basic trade-off scenario, S1, the competitive use of marine resource results in an increase in its economy-wide price. Under the low efficiency scenario, S2, there is a further increase in the marine resource price, while the high efficiency scenario, S3, produces a slightly lower price increase. The increase in the marine resource price would further impact on the production cost of the fishing and offshore wind electricity sectors.

Table 4.7 The marine resource share (%), the percentage change (%) in demand for the marine resource in the fishing and offshore wind electricity sectors, and the economy wide change in marine resource price across different scenarios.

Sectors	Baseline Scenario (S0)	Trade-off scenario (S1)	Low efficiency Scenario (S2)	High efficiency Scenario (S3)
		Marine resource share		
Fishing	-	66.6	60.8	70.8
OWF electricity	-	33.4	39.2	29.2
		Marine resource demand (QMRD)		
Fishing	-	-27.8	-34.2	-23.3
OWF electricity	-	333.6	410.0	279.9
		Price of marine resource (WMR)		
Economy-wide	-	3.6	4.9	2.8

4.2.2.2. Sectoral impacts

The changes in the domestic production and commodity sales are summarised in Table 4.8. The output (QA) of the OWF electricity sector increases by 348% across all scenarios, implying that the share of OWF electricity increases to 27% of total electricity production (from the initial model assumption of 10%). The increase in output is accompanied by a significant decrease in its output price (PA) supported by a government subsidy which drives the shock increase in output.

The model results show that the expansion in OWF production has a negative impact on most sectors although a few sectors may benefit. In all scenarios, the output of the three seafood sectors falls substantially with higher output prices. Without the marine resource trade-off (S0), significant reductions in the seafood production outputs occur, mainly because such small sectors typically have production structures that differ from those of large composite sectors. When the marine resource is explicitly incorporated in the model, the fishing sector is the most significantly affected; the impact is negative, as competition for the marine resource increases the production cost in this sector, leading to a reduction in the domestic output of fish and higher fish prices. Compared to the normal marine resource trade-off scenario (S1), the low efficiency use of marine resource scenario (S2) leads to a lower output of fish with a higher price whereas the opposite happens under the high use efficiency scenario (S3) with the fishing sector being less negatively impacted. The fish processing sector shows the least significant reductions in all scenarios among the three seafood sectors. However, the variations in output reduction across S0 to S3 are quite straightforward, as the fish processing sector reacts to changes in fish supply, with the second largest decrease in output observed in S2 and the smallest in S0. The aquaculture sector shows large reductions in output, mainly due to reallocation of labour and capital rather than decreased fish supply, so the aquaculture sector has least variation across scenarios among the three seafood sectors. In general, the individual scenario results show the impacts from expanding OWFs through the competition between sectors for factors of production, including marine resource. Comparing the results across scenarios suggests that the impacts are mainly from variations in the supply of fish due to the different reallocation of the marine resource.

There is a negative impact on output in the aggregated non-seafood sectors (i.e. agriculture and services) from both supply and demand side (Seung and Kim, 2020). From the supply side, there is competition on limited non-marine resources (i.e., labour and capital). From the demand side, agriculture is an essential input for the fish processing sector (9% in input as shown in Figure 3.3) so that reduction in the fish processing sector indirectly decreases demand to use agriculture as its production input. Therefore, reduction in input results in reduce in outputs of these two sectors. Conversely, there are sectors that benefited from OWFs expansion, i.e. other electricity and industry. The OWF electricity reduces the electricity price so the demand for electricity increases, which can be seen from the higher electricity sales below. As the OWF and other electricity are assumed as complements in the model, high electricity demand also stimulates production of the other electricity sector. Industry is an important input for electricity production, therefore industry is positively impacted due to increased demand from electricity sectors.

Table 4.8 Percentage change (%) in domestic production and commodity sales

	Baseline Scenario (S0)	Trade-off Scenario (S1)	Low efficiency Scenario (S2)	High efficiency Scenario (S3)
Supply	*Domestic production output (QA)*			
Agriculture	-3.2	-3.3	-3.4	-3.3
Fishing	-17.1	-27.2	-33.4	-22.8
Fish processing	-10.2	-13.5	-15.6	-12.1
Aquaculture	-20.4	-21.6	-23.1	-20.7
Other Electricity	32.4	32.2	32.4	32.0
OWF electricity	348.0	348.0	348.0	348.0
Industry	1.8	1.7	1.7	1.6
Service	-1.4	-1.3	-1.4	-1.3
	Price of domestic output (PA)			
Agriculture	0.9	0.9	0.9	0.9
Fishing	0.3	0.8	1.2	0.5
Fish processing	0.1	0.3	0.4	0.2
Aquaculture	0.2	0.1	0.1	0.1
Other Electricity	-5.9	-5.9	-5.9	-6.0
OWF electricity	-58.3	-58.3	-58.3	-58.4
Industry	-0.1	-0.1	-0.1	-0.1
Service	0.4	0.4	0.4	0.4
Demand	*Domestic sales of market commodity (QQ)*			
Agriculture	0.1	-0.1	-0.2	0.0
Fishing	-9.2	-12.3	-14.2	-11.0
Fish processing	-1.5	-2.3	-2.7	-2.0
Aquaculture	-13.9	-15.9	-17.5	-14.9
Electricity	27.7	27.5	27.7	27.3
Industry	2.7	2.6	2.5	2.6
Service	-0.6	-0.5	-0.6	-0.4
	Price of market commodity (PQ)			
Agriculture	0.9	0.9	0.9	0.8
Fishing	1.2	2.7	3.7	2.0
Fish processing	0.5	0.8	0.9	0.6
Aquaculture	0.8	0.8	0.8	0.7
Electricity	-16.1	-16.2	-16.1	-16.2
Industry	0.0	0.0	0.0	0.0
Service	0.4	0.4	0.4	0.4

The change in domestic commodity sales (QQ) follows a similar, but more muted, pattern to that for domestic output. Across all scenarios there is an increase in electricity sales, together with an increased share and reduced price of offshore wind electricity. This results in a substantial decrease in the sales price (PQ) of the electricity commodity. The significant reduction in domestic supply of seafood triggers a slightly higher market sales price and a further decrease in seafood sales in all scenarios. The sales price change directly impacts on household consumption and eventually affect household welfare.

4.2.2.3. Distributional effects on household welfare

The results show significant differences in the distributional impacts on welfare across household groups (see Figure 4.3). In S0 most household groups gain in welfare whereas HH4 experiences a welfare loss. The increased welfare is mostly driven by cheaper electricity prices but for HH4 the welfare loss from expensive seafood outweighs the welfare gain from cheaper electricity. All households have welfare loss from S1 to S3, primarily because of the more expensive seafood. The highest welfare loss occurs in S2 when seafood is most expensive, the lowest in S3 with less expensive seafood. Low income households (HH1 and HH2) show more welfare gain in S0 and have less welfare loss in S1 to S3. The mid- to high-income households (HH3 and HH4) tend to lose most welfare when facing higher seafood prices in S1 to S3, and therefore are more impacted than highest income household HH5.

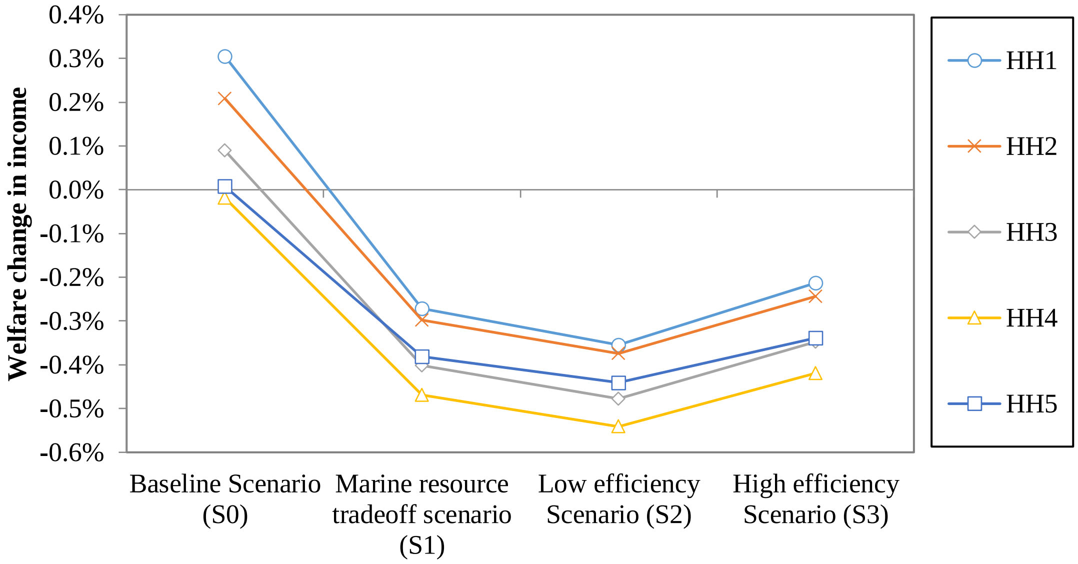


Figure 4.3 Changes in welfare (equivalent variation in income) in all scenarios

4.2.3. Sensitivity analysis

The above results show that the competition over marine resource has significant impact on marine resource price which further changes the production cost for the fishing sector. In the model, the elasticity between marine resource and capital-labour composite ($\boldsymbol{\sigma_a^{va}}$) describes the size of the change in input substitution given a change in the price of the inputs. The development of OWFs for production and marine resource use depends on the value of this elasticity. Therefore, it is necessary to test the results sensitivity with regards to this elasticity for offshore wind electricity sector.

The default setting is that marine resource is the complement of the capital-labour composite. If the elasticity increases, it represents a higher substitution towards the capital-labour composite away from limited and expensive marine resource, and consequently has less impact on seafood sectors. The relationship between the expanding OWF and its sectoral impacts on seafood sectors allowing marine resource trade-off (S1) is determined for three different sets of elasticity of substitution (Table 4.9). The model assumes the elasticity from complement ($\sigma_a^{va} = 0.3$) to low substitution ($\sigma_a^{va} = 2$) and finally high substitution ($\sigma_a^{va} = 5$).

Table 4.9 The sensitivity of selected sectoral outputs (QA) to alternative values of the elasticity $\boldsymbol{\sigma_a^{va}}$ (% change in sectoral output of seafood production and electricity generation sectors)

Production sectors	Default $\sigma_a^{va} = 0.3$	Low substitutable $\sigma_a^{va} = 2$	High Substitutable $\sigma_a^{va} = 5$
Marine resource trade-off scenario (S1)			
Fishing	-27.19	-25.76	-23.83
Fish processing	-13.49	-13.02	-12.39
Aquaculture	-21.64	-21.41	-21.11
Other electricity	32.21	32.21	32.21
OWF electricity	348.00	348.00	348.00

Increasing the elasticity of substitution reduces the negative impact on seafood production sectors (Table 4.9). Under the assumption of high elasticities, the relative price increase in marine resource due to competitive use induces greater replacement of marine resource by the capital-labour composite, implying more capital and labour input to produce the same level of offshore wind electricity and less marine resource movement from the fishing sector. Therefore, the fishing sector displays the most significant change in output correlated to elasticity. Compared to the default elasticity, output reduction in the fishing sector is smaller under higher elasticities. Directly related to fish supply, fish processing also shows less output reduction with high elasticity than in the default situation. There is a slightly lower proportionate output in the aquaculture sector, suggesting less fish are needed as intermediate input. The magnitude of change in output of all sectors is limited and the direction of change is constant (Table 4.9), which demonstrates the robustness of model results.

Furthermore, the sensitivity analysis results show the importance, from a macroeconomic perspective, of technology improvements for reducing negative impacts on seafood sectors. If technology improvements allow higher substitution of marine resource by the capital-labour composite, the seafood sectors could be less negatively impacted, especially the fishing sector. The OWF technology has been improving in recent years, allowing higher and more productive wind turbines without proportionally increasing the marine area required for building more OWF capacity (Rodrigues et al., 2015). This technological development focusses on wind turbine design with the aim to continue increasing turbine size, and component and system reliability, in order to improve wind power plant operations, and to carry more capacity (Ellabban et al., 2014). As the improved technology allows more substitution, the expansion of OWFs could be achieved using less marine resource but more productive wind turbines by putting more labour and capital into the production. Regarding the sensitivity analysis results, technology improvement on OWFs is important to alleviate negative impacts on fish supply terms of the energy-food nexus.

4.2.4. Conclusion

The rapid expansion of OWFs has raised concerns about the conflicting use of marine resource and the potential impacts on seafood supply. It is therefore important that the potential marine resource trade-offs between expanding OWFs and fishing activity are quantified to support marine spatial planning and wider management. The SEMM is created to assess the nexus between OWFs and seafood production. Besides quantifying the inter-sectoral nexus linkages and household welfare distribution, as conventional CGE models could do, a novel marine resource module is created in the

SEMM to better assess the competitive reallocation of marine space between OWFs and fisheries from a macroeconomic perspective.

The first finding indicates that a massive expansion of OWF electricity generation would substantially increase its share in the electricity generation mix, moving Scotland closer to its renewable energy targets. The expansion would improve energy security by increasing domestically produced electricity and providing cheaper electricity to households. This especially benefits lower income households who gain more welfare from reductions in the electricity price.

Meanwhile, massive OWFs expansion would already result in a large negative impact on the seafood sectors purely through macroeconomic linkages. These negative impacts are significantly enhanced when marine resource replacement is taken into account. By creating the innovative marine resource allocation module, the intensified marine resource trade-offs result in significant increases in the production costs of the fishing sector, leading to further reduction in output and higher output prices, which has knock-on effects on the other seafood production sectors.

Due to different consumption patterns, the increased cost of seafood would have more impact on higher income households, reducing their welfare. Furthermore, the comparison between the scenarios generated with and without accounting for marine resource trade-offs shows the importance of the direct spatial conflict between OWFs and seafood when quantitatively assessing the nexus relationships between them. In particular, the marine resource trade-offs would not be identified by conventional CGE models.

This application also runs scenarios to demonstrate that the significant negative impacts on seafood sectors could be mitigated by increasing the marine resource use efficiency through careful marine spatial planning, in which the co-location of OWF and fishing activities is a feasible plan. Moreover, sensitivity analysis shows that improving OWF technology could also help mitigate the negative impacts if marine resource becomes more substitutable by capital and labour.

Compared with application 1, this application 2 takes a step forward in assessing the spatial conflict which fills a critical gap in the quantitative assessment of the socioeconomic impact of OWFs expansion on seafood production from the direct environmental nexus linkage perspective, and also the impact on the whole economy.

The results highlight the potentially significant negative socioeconomic impacts from increased conflict in the use of the marine resource and the need for holistic marine spatial planning. Although the spatial conflict has been included in the nexus assessment, the potential synergy between OWFs and fishing activities is still missing. This brings up the next application of SEMM, which is incorporating natural capital and ecosystem services into the CGE model framework.

4.2.5. Supplementary Information

Table SI 4.4 Percentage changes (%) in imports and exports for all commodities

	Baseline Scenario (S0)	Trade-off Scenario (S1)	Low efficiency Scenario (S2)	High efficiency Scenario (S3)
		Export (QE)		
Agriculture	-5.43	-5.51	-5.58	-5.46
Fishing	-17.34	-27.57	-33.92	-23.10
Fish processing	-10.33	-13.71	-15.86	-12.25
Aquaculture	-20.57	-21.79	-23.20	-20.82
Electricity	65.84	65.69	65.91	65.53
Industry	1.42	1.36	1.43	1.31
Service	-2.59	-2.50	-2.55	-2.46
		Import (QM)		
Agriculture	2.4	2.1	2.0	2.1
Fishing	-6.6	-7.1	-7.4	-6.9
Fish processing	-0.1	-0.4	-0.4	-0.3
Aquaculture	-12.1	-14.3	-15.8	-13.2
Electricity	-9.7	-10.0	-9.7	-10.1
Industry	3.2	3.0	2.9	3.0
Service	0.8	0.8	0.7	0.9

4.3. Application 3

The previous two applications in this thesis of the SEMM have established impacts from OWF development from both established macroeconomic linkages and the spatial conflict for marine resources. However, as reviewed in Section 2.1.2, environmental interactions could also create synergies. Fish stocks could be preserved as fishing activities are reduced inside areas enclosed by OWFs and the OWF infrastructure could also serve as artificial reefs, increasing habitat heterogeneity, creating food chains, providing shelter and nursery areas, thereby further benefitting local fish populations (Langhamer et al., 2009; Stenberg et al., 2015; Westerberg et al., 2013). 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). Therefore, the increased fish stock could potentially bring positive effects on fishing activities and thus benefit food supply.

This application therefore tries to quantify the potential benefits to fishing activities that could come from synergies with OWFs and supplies the missing part in the energy-food nexus assessment by integrating natural capital into SEMM (as described in Section 3.2.3). This is achieved by tracking how economic activities change the use of ecosystem services and thus the natural capital stock levels from an economic perspective. Meanwhile, from an environmental point of view, increasing the natural capital changes the ecosystem services which, in turn, interact with economic activities. In this novel framework, natural capital represented by the fish stock is modelled using a classic fish harvest function whereas a CGE model as described in Section 3.2.3.2 captures the socioeconomic elements.

4.3.1. Scenario simulations

Three scenarios are designed to demonstrate the functionality of the SEMM-Natural Capital model to analyse the two-way linkages between the economy and the natural environment (Table 4.10). Scenario 1 focuses on the impacts on the environment from the economy by increasing the output of OWFs by 348%. The magnitude of this increase is based on the difference between the current capacity of 0.92 GW and a consented capacity of 4.1 GW (Scottish Government, 2019b). This significant increase in output is implemented in the model by adjusting the government subsidy on the OWF electricity sector. Scenario 1 is consistent with the marine resource trade-off scenario (S1) in Application 2. It is used as a benchmark to compare the difference between the outcomes using variants of the model with and without the integration of natural capital into the nexus relationships.

Scenario 2 evaluates how changes in the environment impact 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 situations that do occur in marine reserves. Roberts (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, since closed areas operate as marine reserves in this scenario, it is assumed that there is a 300% increase in fish stock. Changes in fish stock are implemented by changing the parameter α in Equation (3) in Section 3.2.3.2. The increase in fish stock would be expected to bring benefit to the fishing sector and other seafood sectors. Scenario 2 is also a reference scenario that provides a comparison with Scenario 3 because Scenario 2 solely increases the fish stock and models no impacts of OWFs.

Scenario 3 examines the combined impact of a simultaneous 348% increase in output of OWFs together with a 300% increase in fish stock. This scenario simulates the economic potential of co-locating the fishing activity and OWFs, It includes both the negative effects from OWFs and the positive effects from enhanced fish stock. By comparing the results across these three scenarios, this integrated CGE model provides a two-way understanding of the impacts of OWFs on the economy and the environment, and the feedbacks between them.

Table 4.10 Simulated scenarios for Scotland in the SEMM-Natural Capital model for the Application 3.

Model scenario	Impacts	Assumptions made	Shocks in model
Scenario 1	From economy to environment	Expansion of OWFs	348% 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 above two shocks

4.3.2. Results

The results focus on the variables from three areas: production, natural capital and household behaviour. The production results include output (QA), labour and capital demand (QLD, QKD), and the sales price (PQ). The natural capital module includes fish harvested (Q), fishing effort (E) and fish stock (B_1), corresponding with Equation 1 and 2 in Section 3.2.3.2. Household behaviour consists of household income, consumption, and welfare measured as Hicksian equivalent variation. 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).

4.3.2.1. Scenario 1

Scenario 1 outcomes (Table 4.11) show the same variations on the economic side as the results in S1 in Application 2. The results indicate that both electricity sectors increase their production output due to OWF expansion, with correspondingly increased labour and capital demand. As a result of the subsidy, a fall in the 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 and a lower fish harvest. However, at the environmental side, in terms of natural capital, the fish stock actually has a small (0.36%) increase, benefiting from less fish being harvested by the fishing sector. Outputs in the aggregated agriculture and service sector decrease by a smaller proportionate amount. These sectors are mainly affected due to decreasing seafood used as production inputs through the supply chain, as mentioned in Section 4.2.2. For example, processed seafood become food and finally consumed by agriculture and food service (Seung and Kim, 2020). 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 change 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) because their income depends more on wage and capital rent. However, the consumption changes are not consistent with the income changes. All household groups benefit from cheaper electricity and as a result increase their consumption except for HH4, which shows the highest decrease in income and a slight reduction in consumption. The same conclusion can be drawn from these results as from the previous two applications; lower income households tend to purchase more due to cheaper electricity while the consumption of higher income households are more sensitive to increased seafood sales prices. The variation in household consumption behaviour is that higher income households tend to have smaller change in consumption as they have relatively more disposable income to spend against commodity price changes. Similar variations also exist in household welfare changes as most household groups gain welfare (£3.87 to £28.47 million) except for HH4, which shows a loss in welfare (£6.19 million).

Table 4.11 Relative changes (%) from baseline values for key parameters under Scenario 1 - 348% increase in OWF output

Production Sectors	Production output (QA)	Labour demand (QLD)	Capital demand (QKD)	Commodity sales (QQ)	Sales price (PQ)
Agriculture	-3.18	-2.79	-3.46	0.12	0.87
Fishing	-17.10	-16.83	-17.41	-9.17	1.19
Fish processing	-10.13	-9.98	-10.61	-1.53	0.50
Aquaculture	-20.40	-20.26	-20.81	-13.93	0.84
Other electricity	32.40	30.13	29.23	27.72	-16.10
OWF electricity	348.01	338.88	335.84		
Industry	1.75	1.86	1.15	2.72	-0.02
Service	-1.37	-1.14	-1.82	-0.55	0.43
Natural capital module	Fish harvested (Q)	Fish effort (E)	Fish stock (B)		
Fishing	-17.25	-17.25	0.36		
Household	Income	Consumption	Welfare		
HH1	0.00	0.53	28.47		
HH2	-0.06	0.36	27.61		
HH3	-0.12	0.20	19.86		
HH4	-0.16	-0.04	-6.19		
HH5	-0.04	0.03	3.87		

4.3.2.2. Scenario 2

Scenario 2 model results (Table 4.12) indicate that in general, increasing fish stock due to closed area 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 commercial fishing production output. Increased fish stock makes fishing activities more productive with not only increases in harvested fish but also decreases in the labour and capital needed as production inputs. The impacts on other seafood sectors are less significant in percentage terms through being capital-intensive (as shown in Figure 3.3); the aquaculture sector particularly benefits from released capital from the fishing sector. This is indicated by the biggest variation in capital demand and thus apart from fishing, this sector experiences the largest increase in output. With more fish available as a production input, the fish processing sector and the agriculture sector increase their outputs. The remaining sectors also benefit slightly from released capital from the fishing sector, presenting slight 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 minor (less than 0.02% generally). As for household welfare change in monetary value, all household groups make a small welfare gain, ranging from £0.32 million to £5.54 million. The higher income households have the highest welfare gain. This finding is also consistent with previous results in Application 2 that higher income households tend to be more sensitive to seafood sales price changes.

Table 4.12 Relative changes (%) from baseline values for key parameters under Scenario 2 - 300% increase in fish stock

Production Sectors	Production output (QA)	Labour demand (QLD)	Capital demand (QKD)	Commodity sales (QQ)	Sales price (PQ)
Agriculture	0.11	0.09	0.12	0.04	-0.03
Fishing	31.92	-25.85	-25.83	0.07	-0.04
Fish processing	0.07	0.05	0.09	0.03	-0.01
Aquaculture	1.30	1.28	1.31	0.69	-0.09
Other electricity	0.14	0.12	0.15	0.11	-0.02
OWF electricity	0.11	0.10	0.13		
Industry	0.05	0.04	0.07	0.09	0.01
Service	0.02	0.00	0.03	0.02	0.00
Natural capital module	**Fish harvested (Q)**	**Fish effort (E)**	**Fish stock (B)**		
Fishing	122.51	-25.83	-0.42		
Household	**Income**	**Consumption**	**Welfare**		
HH1	0.00	0.01	0.32		
HH2	0.01	0.02	1.28		
HH3	0.02	0.03	3.07		
HH4	0.02	0.04	5.24		
HH5	0.02	0.03	5.54		

4.3.2.3. Scenario 3

In Scenario 3, the impacts are mainly dominated by the expansion of OWFs so that the results are similar to Scenario 1 (Table 4.13), except for the fishing sector. 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 electricity output is slightly (~0.03%) 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 (4.08%) while reductions in fish processing (2.20%) and aquaculture (0.31%) outputs are less than the sums in Scenarios 1 and 2. This is because the production and consumption functions in the model are nonlinear, which causes the cumulative effect to be different from the simple sums of the effects from component shocks (Waters and Seung, 2010).

Table 4.13 Relative changes (%) from baseline values for key parameters under Scenario 3 - Combined 348% increase in OWF output and 10% increase in fish stock

Production Sectors	Production output (QA)	Labour demand (QLD)	Capital demand (QKD)	Commodity sales (QQ)	Sales price (PQ)
Agriculture	-3.07	-2.69	-3.35	0.21	0.85
Fishing	18.89	-32.92	-33.38	-7.08	0.17
Fish processing	-7.86	-7.74	-8.37	-1.17	0.32
Aquaculture	-18.79	-18.66	-19.20	-12.26	0.82
Other electricity	32.50	30.22	29.34	27.81	-16.11
OWF electricity	348.01	338.85	335.89		
Industry	1.76	1.85	1.17	2.80	-0.01
Service	-1.37	-1.14	-1.80	-0.53	0.43
Natural capital module	Fish harvested (Q)	Fish effort (E)	Fish stock (B)		
Fishing	100.23	-33.26	-0.26		
Household	Income	Consumption	Welfare		
HH1	0.00	0.54	28.75		
HH2	-0.05	0.37	28.46		
HH3	-0.10	0.23	22.10		
HH4	-0.14	-0.01	-2.45		
HH5	-0.03	0.05	7.74		

All household groups experience a slightly decreased income, the variations in which have similar patterns as in Scenario 1. The percentage decrease in income is again greatest for the three mid-income household groups. Consumption increases are higher in lower income households while HH4 has a consumption reduction. The welfare distribution again follows consumption. Most households make welfare gains ranging from £7.74 million for the highest income household group (HH5) to £28.75 million for the lowest income household group (HH1). The impacts on welfare are also not simply additive. Compared to the sums of welfare changes in Scenarios 1 and 2, HH2, HH3 and HH5 gain less welfare while HH4 loses more welfare.

4.3.3. 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 resources.

In this application, the integration of natural capital in the SEMM is used to assess how OWF development impacts seafood production and the wider economy by quantifying these impacts at the macroeconomic level. The model results suggest that expansion of OWFs has negative impacts on fishing production, as also indicated by previous applications. However, this reduction in fishing output actually conserves the fish stock to a small extent, which cannot be tracked in previous applications. The increase in fish stock due to the marine reserve effect from closed areas by OWFs could be translated into small economic benefits, with the fishing sector showing an increase in production. Furthermore, the combined effects of OWFs expansion and increased fish stock demonstrate that if the fishing sector could access these increased fish stocks, it would be sufficient to mitigate part of the negative impacts of OWFs on fishing production and the knock-on impacts on other seafood productions.

Compared to the previous two applications, this application further fills the gap in assessing the potential synergies between OWFs and fishing activities in the nexus linkage. By capturing two-way interrelationships among components of environmental and economic systems, this integrated framework can provide valuable insights into the potential positive and negative impacts of OWFs expansion on the whole economy and the environment. These outcomes highlight the conflicts and synergies between OWFs and seafood production from an energy-food nexus perspective as well as potential application of the CGE modelling framework to improve natural capital and ecosystem services valuation. Therefore, the model could serve to generate awareness among policy makers of holistic thinking in the future development of clean energy infrastructure and the role that natural capital and ecosystem services can play in the economy.

5. Discussion

In the preceding results chapter, three applications of the novel CGE model developed for this thesis have been used to explore the implications of the ambitious plans to grow OWFs for the Scottish economy. This has been considered from the energy-food nexus perspective, with the impacts of OWF expansion on energy security and security of seafood supply assessed through indirect macroeconomic linkages and direct environmental linkages (as reviewed in Chapter 2 Section 2.1). This chapter discusses the main findings and achievements in the thesis as a whole.

The major methodological achievements regarding the CGE model development are firstly reviewed in this chapter in terms of achieving the first objective of the thesis, which is the development of an integrated modelling framework that encompasses the relevant linkages of the energy-food nexus. The development of the modelling framework begins with the testing of a basic CGE model structure (Application 1) for the indirect economic implications resulting from nexus linkages; progresses to the creation of a marine resource allocation module (Application 2) to understand the environmental linkages in terms of direct spatial conflict; and finally ends with the integration of natural capital into the CGE model (Application 3) to explore synergies in the environmental nexus linkage.

Then the findings from the Results chapter are interpreted in terms of food and energy security, mainly focusing on availability and affordability, and further implications on the wider economy, mainly focusing on household behaviours and welfare distribution. This section achieves the second and empirical objective of the thesis which is to identify and assess the macroeconomic and environmental linkages between offshore wind energy and seafood production.

Next, last objective of the thesis, the policy implications from model results, are discussed to explore the potential of CGE models, in enhancing quantitative nexus thinking, importance of integrating the natural capital and ecosystem approaches into economic analysis, making marine planning better, and evaluating other marine renewables.

The last section discusses the limitations of the current SEMM model and the directions for future research.

5.1. Major results and achievements

5.1.1. Methodological improvements

Chapter 2 reviews previous studies and identifies a crucial gap in the quantitative assessment of the environmental and economic linkages between expansion of OWFs and seafood productions from an energy-food nexus perspective. This thesis therefore fills this gap by developing a Scottish Economy Marine Model (SEMM) that can quantitatively assess the energy-food nexus linkages between OWFs and seafood productions. It is also corresponding to the first research objective of this thesis. Three significant methodological advances in this model allow better understanding of the nexus linkages, particularly at the macroeconomic level (Figure 5.1).

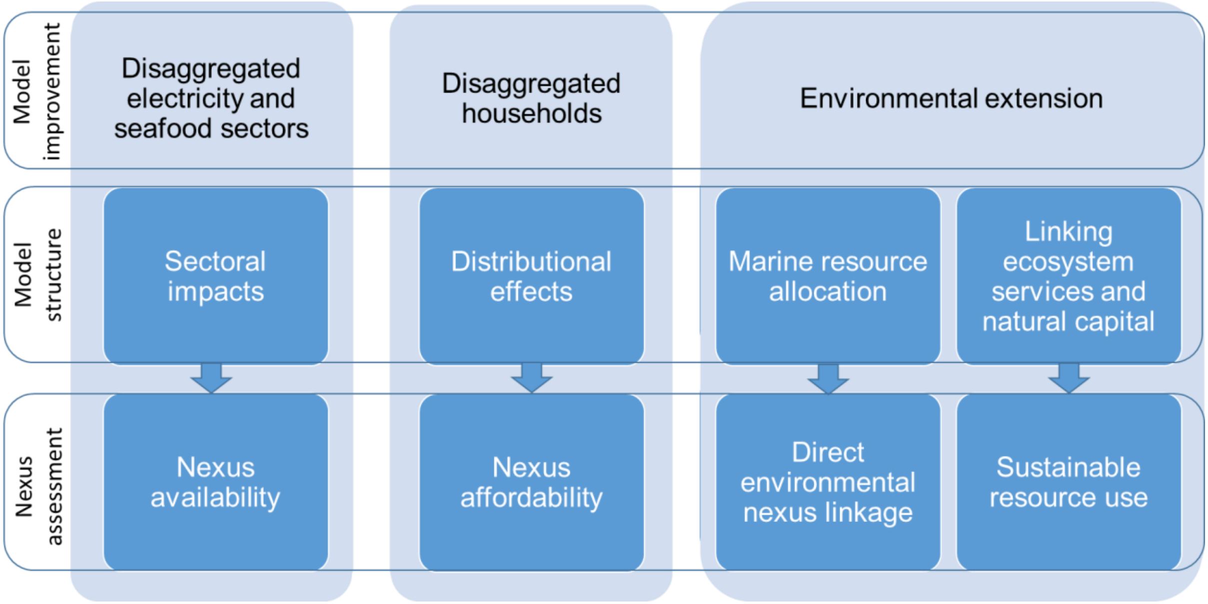


Figure 5.1 Summary of three main methodological improvements in SEMM model in this thesis

Most CGE models for nexus assessment is land based (e.g. Arndt et al., 2012; Banse et al., 2008; Hertel et al., 2010; Timilsina et al., 2012) and no CGE model has been applied to assess the nexus linkages between OWFs and seafood productions before. The SEMM is therefore the first CGE model for assessing the nexus linkages in the marine environment.

5.1.1.1. Basic structure improvement

To assess the nexus linkage between OWFs and seafood production, the SEMM model is built from scratch specifically for this thesis. It is the first CGE model concentrating on the energy-food nexus regarding OWFs and seafood. Its theoretical structure departs from the International Food Policy Research Institute (IFPRI) Standard CGE model framework (Löfgren et al., 2002). This kind of traditional model structure assumes that all the agents perform under an optimizing behaviour, there is homogeneity of degree zero in prices and incomes, and an appropriate set of prices for commodities and factors clears all the markets. Although there are CGE models relaxing some of the assumptions in the traditional structures, allowing such as imperfect competitive market (e.g. Roson, 2006), oligopolistic competition (e.g. Orlov and Grethe, 2012), and decreasing returns to scale (e.g. Fraser and Waschik, 2013). The development of the SEMM follows the traditional CGE model structure as that is sufficient to assess the resource constraint in the nexus linkage. The extra attention has been paid in this thesis on how to develop the CGE model to explore in more detail that environmental factors that shape the nexus linkage between OWFs and seafood production.

First, there is disaggregation of three seafood sectors and the OWF electricity sector to explore the nexus linkages between them. The specific disaggregation of electricity and seafood sectors in SEMM offers deeper insight into impact at sectoral level in terms of energy security and fish supply, with a focus on availability and affordability. Availability under the different scenarios is measured through the sectoral outputs compared with the base year to highlight changes in the supply and demand of goods. This fills a gap in assessing the impacts of OWFs as previous CGE models for OWFs only focus on their general macroeconomic impacts such as on GDP and employment (Graziano et al., 2017; Lecca et al., 2017), which ignores the sectoral impacts on seafood sectors. These sectoral impacts are potentially substantial under resource constraint (e.g., limited labour, capital, or marine resource) through the macroeconomic linkages from both production and consumption side, which are implied by nexus assessment between biofuel and agriculture production (Arndt et al., 2012; Banse et al., 2008; Hertel et al., 2010). Hence, the disaggregation of three seafood sectors and two electricity sectors enhance the SEMM to assess the changes in nexus availability.

Second, disaggregation of five household quintiles enables SEMM to concentrate on nexus affordability. Affordability capitalises on the CGE model’s ability to allow variations in prices of goods in an economy and is an improvement on the commonly used fixed-price economic models. In particular, five households groups based on income quintiles allow the SEMM to analyse the affordability to households and welfare distribution, offering insights into the social dimension of OWFs impact from the nexus perspective. As reviewed in Chapter 2, previous CGE model applications to marine renewables have not pay attention to distributional effects across households (e.g. Allan et al., 2008, 2014; Graziano et al., 2017; Lecca et al., 2017). Only a few CGE model applications to fishery concentrated on distinguished household groups and their welfare (e.g. Carvalho et al., 2011; Hoagland et al., 2015; Jin et al., 2012; Pan et al., 2007). Therefore, the disaggregation of household groups makes the SEMM useful for understanding the different consumption patterns of households with different income, particularly the impacts of electricity price changes on fuel poverty and the impacts of seafood price changes on households' seafood intake.

Third, the basic SEMM structure has three different degrees of capital mobility to distinguish three separate conceptual time periods. A main distinction between the three closures relates to the treatment of capital stocks encountered in the standard economic approach: the short run is a period in which the capital stock is fixed for individual sectors; the long run is a period in which all capital can be optimally adjusted between sectors; the extra-long-run refers to a period when capital stocks are flexible to adjust to get into the equilibrium state so that the level of investment also adjusts at exactly the same rate. These three capital closures relax the constraint on capital mobility in order to compare the impacts of different capital availability on nexus assessment. Such different closures also correspond to Marshallian factor market short and long run characteristics (Bergman, 1982; Britz and Roson, 2018). Since the resource limitation is the major concern in the nexus approach, comparing the results from different closures makes the nexus assessment associated with different capital allocation constraint so that it can cover wider scope of the assessment (Banse et al., 2013).

However, the above basic SEMM structure lacks the ability to assess the direct environmental linkages between OWFs and seafood sectors, regarding their spatial conflicts over limited marine areas (Mackinson et al., 2006; Stelzenmüller et al., 2016) and synergies due to the closed areas and artificial reef effects (Bergström et al., 2013). The basic SEMM only allows a general assumption on increasing fishing effort due to displacement of fishing activities as a results of the fishing community being forbidden access or reluctant to fish within OWF areas (Gray et al., 2016; Hooper et al., 2015), which is implemented in the model through decreasing the efficiency of fishing activities (Application 1 Scenario 3). The general assumption on displacement of fishing effort is ambiguous and largely confined to three seafood sectors. As reviewed in Chapter 2, the most works regarding the environmental linkages between OWFs and seafood productions are qualitative (Alexander et al., 2013a, 2013b; Gray et al., 2016; Hooper et al., 2015; Mackinson et al., 2006; Reilly et al., 2015), only two quantitative studies have done the trade-off analysis but ignores the wider economic impacts (White et al., 2012; Yates et al., 2015). One advantage of the CGE model is that it cannot only capture the economic linkages recorded in the market transactions but also be extended to include more factors and link with ecological/biological models to consider environment resources, which is the key focus of the development of the environmentally extended SEMM model.

5.1.1.2. Creation of marine resource allocation module

Under this circumstance, a marine resource allocation module is built and improves the basic SEMM. 'Marine resource' is created to reflect the direct environmental nexus linkage between OWFs and fishing activities. As a newly created production factor, marine resource is under fully competitive use between OWFs and the fishing sector. The marine resource allocation module takes advantage of the price mechanism in the CGE model through which expansion of OWFs would bid away marine resource so that a reduced amount of marine resource is left for fishing activity and it has a higher price, resulting in increased production cost and falling production. It describes the necessity of marine resource as a factor in OWF electricity and fishing production and can highlight the significant trade-offs between them, especially when comparing the results with and without introducing the marine resource module (S0 and S1 in Application 2).

The novelty of the above marine resource allocation module is that it visualises the spatial conflict between OWFs and fishing activities by considering it as a production factor in the CGE model, similar to the role of land as a production factor for both biofuel and agriculture production in terms of the terrestrial energy-food nexus. Modelling the land use has been widely applied in CGE models before (Kretschmer and Peterson, 2010), but has not been applied to marine. Doing so gives insights into how to allocate resources in the optimal way, under marine resource constraints. Unlike land, marine resource is not a classic production factor in the CGE model, so a few assumptions have been made to implement the valuation of marine resource. The value of marine resource is assumed to be the price paid by marine activities for the licenses to use marine areas (Scottish Government, 2018c).

The creation of marine resource also adds one more level of nesting to the value-added nest (as shown in Figure 3.8), allowing more flexibility of marine resource substitution with capital and labour. It allows the model to describe subsets of inputs as either complements or substitutes within the production process, which gives more flexibility to test the sensitivity of how changes in marine resource impacts the model results. It further extends the results implications to marine spatial planning regarding the OWF technology improvement (as discussed in Section 4.2.3).

5.1.1.3. Integrating natural capital and ecosystem services

The above two modelling frameworks do not include the potential positive impacts OWFs could bring to fishing activity, through increasing fish stock from the closed areas acting as marine reserves and the artificial reef effect. This needs further extension of the CGE model to integrate the natural resource into its framework. Including an environmental dimension in the energy-food nexus assessment can also improve sustainability regarding the use of ecosystem services and natural capital. Therefore, an 'Environment' sector is created in the SEMM as the source of natural capital to provide ecosystem services as inputs for production sectors.

In the case of fishing activity, the fish harvested is the ecosystem service provided by fish stock which is the natural capital. There are previous CGE models that have been extended frameworks with links to ecosystem services such as harvested fish though not to natural capital such as fish stock with the CGE model (Finnoff and Tschirhart, 2008; Jin et al., 2012). Natural capital has been integrated into CGE model only for agriculture (Allan et al., 2018) and forest (Ochuodho and Alavalapati, 2016). The theoretical method of integrating ecosystem services and natural capital approach of aquatic resources was only mentioned by Banerjee et al. (2016) but has not been practically applied, which is adopted in the SEMM of this thesis. A classic fish harvest function links the fish harvested with the existing fish stock while a fish population dynamic function is applied to simulate the changes in fish stock after a certain amounts of fish have been harvested by fishing activities. By linking the fish harvest function with the fishing production function, the harvested fish is interpreted as a production input used by the fishing sector, whereas the fishing effort is a function of labour and capital. Both fish stock and harvested fish are then integrated as endogenous variables in the SEMM to create a link between economy and environment.

This SEMM-Natural Capital model is now capable of quantifying the impacts of changes in the economy on the environment as well as the impacts of changes in fish stock on the overall economy. Therefore, model results could report changes in fishery production, ecosystem state, and economic variables. Linking natural capital and ecosystem services with the CGE model can 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 (Allan et al., 2018; Banerjee et al., 2016a; Comerford, 2017). Adding the environment sector explores the challenges involved in integrating natural capital and ecosystem services into the CGE model. Meanwhile, this SEMM-Natural Capital framework is useful to evaluate the effect of the inclusion of the environmental dimension on nexus assessment and is capable of indicating the sustainable resource use.

In conclusion, the development of the basic SEMM framework and two additional modules to the modelling framework follows an ordered and progressive approach to gaining deeper insight into the energy-food nexus between OWFs and seafood productions, from a purely macroeconomic analysis to an integrative economic-environmental analysis. The model development starts from focusing on economic linkages using the basic model structure, then includes spatial conflict using a marine resource allocation module, and finally links directly with the environment by integrating natural capital and ecosystem services into the model. These modelling frameworks specifically capture the nexus linkages affected by the expected expansion of OWFs to better understand the trade-offs and synergies with seafood productions. The SEMM in this thesis fills the gap of quantitative assessment of macroeconomic impacts of OWFs on seafood productions and wider economy in the economic dimension, on the distributional effects on households in the social dimension, and on the fish harvested and fish stock in the environmental dimension, thus covering all three dimensions from the nexus perspective. Furthermore, these modelling frameworks could be applied to other energy-food nexus issues, e.g. other marine renewable energy technologies, as long as the data required is available. Generally, the model results could facilitate the consideration of nexus linkages between OWFs and seafood productions by reporting the main socioeconomic factors (e.g. output, price, sales, and household welfare). The next section discusses the main findings from the three model applications.

5.1.2. Findings

This section discusses the major findings of this thesis using the three SEMM applications facilitated by its major methodological improvements, which also aims to meet the second research objective. The specific sectoral impacts on energy security and fish supply in the first two parts are analysed from an energy-food perspective to better minimise the trade-offs and maximize the synergies. Disaggregation of households to assess the distributional effects on households, which are discussed in the third part.

5.1.2.1. Sectoral impacts on energy security

There are high expectations for the role of OWFs in reaching the net-zero emission target and in increasing energy security by reducing the UK's dependence on fossil fuels for electricity generation (CCC, 2019). It is therefore important to analysis the impacts of expansion of OWFs on energy security. In general, the model results show that the expansion of OWFs could increase the availability, affordability and resilience of electricity, thus addressing all three aspects of energy security (Valentine, 2011). The main findings from three applications in terms of energy security are summarised in Table 5.1. In general, energy security is enhanced (shown as ↑ in Table 5.1) in most cases as more OWFs increase the availability by supplying more electricity and the affordability by decreasing electricity price. Increased domestic electricity supply also means less dependence on imported energy, together with increasing share of OWFs in domestic electricity generation, which minimize energy supply risk system in the event of an accident and thus enhances energy resilience (Valentine, 2011).

The first main finding from the simulations performed in Application 1 is the influence of different closure rules on the results. The analysis is performed with three different closures in order to check how technical issues can underestimate or overestimate the impact of the OWF expansion. The results suggest that the impacts of developing OWFs on macroeconomic variables under short-run closure are small but not negligible, high cost and fixed sectoral capital would prevent OWFs from expanding and decrease energy security. This is mostly because the rigidity of capital is not sufficient to meet the high production cost so that the electricity production reduces. When capital is flexible to move, electricity production could attract capital to increase output in the long run and even to a larger extent with sufficient capital stock in the extra-long-run.

It can be seen from the above results that different capital mobility has evident impact on the magnitude and direction of the model results, which is a potential criticism of the model (Mercure et al., 2019). However, such differences do not suggest that the model results are unreliable, but rather highlight the different economic status, regarding the different mobility of capital (Bergman, 1982; Teresa et al., 2017). As a limited resource, capital is the constraint and the model results demonstrate how an improved access to capital affects development of OWFs and the corresponding impacts on the economy. More capital that is available would be conductive to OWFs expansion and increase energy security, especially when the cost is higher. Therefore, although a CGE model cannot provide a forecast, the model results serve as indications of the relative scale of effects and distribution of impacts under different economic structures (Allan et al., 2008). In addition, such findings are also potentially quite important from the point of view of building economic models, as they contribute to a better understanding of the impacts of different mobility of capital on the economy in the CGE modelling (Banse et al., 2013).

Table 5.1 Summary of impacts of OWFs expansion on energy security in terms of energy availability, affordability and resilience, presented by percentage changes in production output, sales price, imports and shares in electricity generation (Note: ↑ means enhanced, ↓ means decreased, and – means no change for energy security)

Applications	Energy security	Energy availability			Energy affordability			Energy resilience			
	Variables	OWF production output (QA)			Electricity sales price (PQ)			Imported electricity (QM)			% in electricity generation
	Scenarios	Short-run	Long-run	Extra-long-run	Short-run	Long-run	Extra-long-run	Short-run	Long-run	Extra-long-run	
Application 1	S1: higher cost	↓ (-0.3%)	↑ (5.3%)	↑ (5.7%)	↓ (1.2%)	↑ (-0.7%)	↑ (-0.8%)	↓ (4.1%)	↓ (2.5%)	↓ (2.5%)	– (10%)
	S2: lower cost	↑ (0.8%)	↑ (5.8%)	↑ (6.3%)	↑ (-0.5%)	↑ (-2.1%)	↑ (-2.2%)	↑ (-1.0%)	↑ (-2.3%)	↑ (-3.5%)	– (10%)
Application 2	S0: without allocation		↑ (348.0%)			↑ (-16.1%)			↑ (-7.4%)		↑ (27%)
	S1: with allocation		↑ (348.0%)			↑ (-16.2%)			↑ (-7.5%)		↑ (27%)
Application 3	S1: massive expansion		↑ (348.0%)			↑ (-16.1%)			↑ (-9.7%)		↑ (27%)

The second main finding compares the impacts of decreasing cost of OWFs. It confirms that the CfD scheme serves to simulate OWF electricity production and brings down the electricity price slightly when the cost of OWF electricity (£64/MWh) is still higher than average electricity wholesale price (£48/MWh). One advantage of developing renewable energy is the expectation to bring economic benefits (Phimister and Roberts, 2017), but Application 1 results show that economic benefits depend on the circumstances. Although the CfD scheme promotes OWF electricity production, it is in a costly way since GDP decreases. This scenario reflects a path to decarbonisation that is inherently expensive. However, the lower than average cost that is now achievable could support OWF expansion and further reduce the electricity price. It indicates that OWFs would only start benefiting the economy when their cost is decreased sufficiently to become subsidy-free. This is coherent with the expectations of OWFs to bring benefits to the economy by stimulating investment and creating employment (Graziano et al., 2017; Lecca et al., 2017; McNeil et al., 2013). The results from extra-long-run demonstrates such expectation that OWFs would increase investment and thus GDP when the capital stock increases as a result of expanding OWFs. In particular, Lecca et al. (2017) used a dynamic CGE model to assess the impacts of 30% decreasing cost of OWFs on the UK economy and found that it would significantly stimulate this sector’s output (about 50% increase). Furthermore, their work also made projection for UK that cost of OWFs below £90/MWh would be required to achieve 22 GW offshore wind capacity by 2030. Now the record-low OWFs price (£41/MWh) shows that offshore wind is already an economically feasible technology, which means that there is greater potential to reach the capacity of 30 GW by 2030 according to the recent UK Government sector deal (HM Government, 2019). The record-low price is an incentive to significantly increase the offshore wind capacity and energy availability with positive impacts on the Scottish economy at the macro scale in the near future.

Therefore, Application 2 and 3 simulates the impacts of significantly increasing the offshore wind capacity on energy security with a more flexible SEMM structure – allowing substitution between OWF electricity and other electricity. It means significant increases in the share of OWFs in the overall electricity generation mix. This will support energy resilience considering that offshore wind resources are stronger and steadier than onshore wind resources (Esteban et al., 2011; Sovacool, 2013) and renewable energy technologies become more decentralized, with lower impacts from technological malfunctions (Valentine, 2011). The massive expansion of OWFs further increases energy security through supply of more domestically produced and cheaper electricity. When considering the marine resource trade-offs between OWFs and fishing activities, the changes in electricity sales and prices are not as significant as without marine resource. This is because the competition over marine resource increases the production cost which impedes the OWFs expansion slightly, only if they need to pay to use marine resource.

Although the model has a flexible structure to allow substitution between OWF electricity and other electricity based on prices, their actual substitutability in practice is more complex due to technical constraints in areas such as electricity storage and grid connection (Madrigal and Stoft, 2012). A sensitivity analysis is therefore performed run in Application 1 to test the sensitivity of the trade-off that the national grid is prepared to make across different generation types, which is represented by elasticity of substitution between the two electricity production sectors in the model. The results suggest that as technology improves (simulated by increasing elasticity in the model), OWFs could have greater replacement of other electricity and account for a larger share in total electricity generation and thus increase energy resilience.

5.1.2.2. Sectoral impacts on fish supply

Seafood makes an important contribution to fish supply as a source of protein, essential fatty acids and micronutrients (Hall et al., 2013; Smith et al., 2010). Globally, 17% of human protein intake came from fish resources in 2015, where 150 g of fish provides about 50 to 60% of an adult’s daily protein requirements (FAO, 2018). Although OWFs expansion would increase energy security, it would have both negative and positive impacts on seafood production as shown by the model results, potentially affecting fish supply in terms of availability, affordability and utilization (Ericksen, 2008). The seafood sector results from our model most relevant to fish supply include the production outputs (relevant to availability), the sales prices (relevant to affordability) and household consumption (relevant to utilization). The main findings from Application 1, 2 and 3 in terms of fish supply in three seafood sectors are summarised in Table 5.2. It appears that overall fish supply is negatively affected by OWF expansion, as the availability, affordability and utilization of seafood all decrease (shown as ↓ in Table 5.2) in most scenarios analysed.

Table 5.2 Impacts of OWFs expansion on fish supply in terms of availability, affordability and utilization, represented by percentage changes in production output, sales prices, and household consumption for the three seafood sectors (↑ means enhanced, ↓ means decreased, and – means no change for fish supply)

			Availability			Affordability			Utilization		
			Production output			Sales prices			Household consumption		
Applications	Scenarios		Fishing	Fish processing	Aquaculture	Fishing	Fish processing	Aquaculture	Fishing	Fish processing	Aquaculture
Application 1	S1	Short	↓ (-0.0)	↑ (0.1)	↓ (-0.0)	↓ (0.1)	↓ (0.0)	↓ (0.1)	↓ (-0.2)	↓ (-0.2)	↓ (-0.6)
		Long	↓ (-2.8)	↓ (-1.4)	↓ (-5.5)	↓ (0.2)	↓ (0.1)	↓ (0.3)	↓ (-0.2)	↓ (-0.2)	↓ (-0.6)
		Extra-long	↓ (-0.8)	↓ (-0.8)	↑ (0.1)	↓ (0.0)	↓ (0.0)	↑ (-0.1)	↓ (-0.1)	↓ (-0.1)	↓ (-0.3)
	S2	Short	– (0.0)	↓ (-0.0)	– (0.0)	– (0.0)	– (0.0)	– (0.0)	↑ (0.1)	↑ (0.1)	↑ (0.2)
		Long	↓ (-3.4)	↓ (-1.9)	↓ (-5.1)	↓ (0.2)	↓ (0.1)	↓ (0.2)	– (0.0)	↓ (-0.1)	↓ (-0.1)
		Extra-long	↓ (-0.9)	↓ (-1.1)	↑ (2.1)	– (0.0)	– (0.0)	↑ (-0.2)	↑ (0.2)	↑ (0.1)	↑ (0.5)
	S3	Short	↓ (-1.1)	↓ (-0.1)	– (0.0)	↓ (0.2)	– (0.0)	– (0.0)	– (0.0)	– (0.0)	– (0.0)
		Long	↓ (-13.5)	↓ (-4.2)	↓ (-1.5)	↓ (1.7)	↓ (0.3)	↓ (-0.1)	↓ (-0.3)	↓ (-0.1)	– (0.0)
		Extra-long	↓ (-13.7)	↓ (-4.3)	↓ (-2.2)	↓ (1.7)	↓ (0.3)	↓ (-0.1)	↓ (-0.3)	↓ (-0.1)	– (0.0)

Application 2	S0	↓ (-17.1)	↓ (-10.2)	↓ (-20.4)	↓ (1.2)	↓ (0.5)	↓ (0.8)	↓ (-0.1)	– (0.0)	↓ (-0.2)
	S1	↓ (-27.2)	↓ (-13.5)	↓ (-21.6)	↓ (2.7)	↓ (0.8)	↓ (0.8)	↓ (-0.8)	↓ (-0.5)	↓ (-1.2)
Application 3	S1	↓ (-17.1)	↓ (-10.1)	↓ (-20.4)	↓ (1.2)	↓ (0.5)	↓ (0.8)	↓ (-0.1)	– (0.0)	↓ (-0.2)
	S2	↑ (31.9)	↑ (0.1)	↑ (1.3)	↑ (-0.0)	↑ (-0.0)	↑ (-0.1)	– (0.0)	– (0.0)	↑ (0.1)
	S3	↑ (18.9)	↓ (-7.9)	↓ (-18.8)	↓ (0.2)	↓ (0.3)	↓ (0.8)	↑ (0.1)	↑ (0.1)	↓ (-0.1)

From the energy-food nexus perspective the first negative impact on fish supply is that expanding OWFs would shift production resources, such as labour, capital, and especially the marine resource (area), away from seafood production. These shifts would affect the production cost for seafood sectors through macroeconomic linkages and seafood related fish supply. It is the classic energy-food nexus thinking originated from biofuel and agriculture, which biofuel will tend to affect outputs and prices of agricultural commodities (Banse et al., 2008; Timilsina et al., 2012; Zilberman et al., 2013). Application 1 confirms the existence of macroeconomic linkages between OWFs and seafood production through the reallocation of limited production factors (i.e. labour and capital) so that the seafood sectors are negatively affected by the expansion of OWFs. Given that the three seafood sectors are small production sectors which have very different cost structures from the average, they are more sensitive to the movement of labour and capital and therefore suffer more negative impacts from it. Furthermore, the extent of such negative impacts depends on how constrained these production factors are. When capital is immobile in the short-run, the expansion of OWFs is limited so that it has only limited impacts on seafood production. When inter-sectoral mobility of capital is allowed in the long-run, the negative impacts on seafood sectors become more evident as extra capital needed in OWF production is pulled from them. When capital stock is no longer the constraint, seafood sectors have less significant negative impacts from OWFs expansion but labour is the limiting factor so that the negative impacts still exist. In conclusion, the systematic variation of factor mobility indicates that regardless of different degree of capital mobility there is generally negative nexus linkages between OWFs and seafood production through the indirect macroeconomic linkages.

There is another concern about energy impact on fish supply in terms of the energy-food nexus through macroeconomic linkages. Previous studies have shown that a recent food price increase (including for seafood) was strongly influenced by increasing energy (mainly fossil fuels) costs given that energy is an important input for food production (Pelletier et al., 2014). The most important energy input for modern industrial fisheries is fuel (for the boats) which typically accounts for between 75% and 90% of total energy inputs (Tyedmers, 2004). Therefore, rising fuel prices more potentially tends to result in reduced fishing effort and further less fish supply (FAO, 2015). As for aquaculture, energy inputs vary significantly with different species (e.g., 2.9% – 10.4% for mollusc, 35% for shrimp) but in general the electricity inputs are not major component in aquaculture production (Sturrock et al., 2008). Fuel and energy requirements for the processing sector also vary widely, and the energy costs are substantially lower in overall terms than those for capture fishing activities (FAO, 2015). Although fuel is essential energy input for seafood productions, electricity is yet relatively insignificant production input for the seafood sectors, accounting for 4%, 1% and 5% of total production inputs for fishing, fish processing and aquaculture respectively (based on 2013 Scottish SAM data). The results from Application 1 also suggest that the cost of OWF electricity has no observable direct impact on seafood production.

Many previous works have demonstrated the negative impacts of OWFs on fishing activities, qualitatively (e.g. Gray et al., 2016; Hooper et al., 2015; Mackinson et al., 2006; Stelzenmüller et al., 2016). This thesis takes these qualitative impacts and transforms them into economic shocks to make quantitative assessment. The impact of displacement of fishing effort by OWFs on seafood production is addressed in Application 1. Using the basic SEMM structure, decreasing fishing effort substantially reduces fishing output (-13.5%) and has knock-on negative effects on the fish processing and aquaculture production. These negative impacts purely through macroeconomic linkages are indirect and limited. Therefore, the direct spatial conflict between massive expansion of OWFs and fishing activities is considered in Application 2 through the creation of a new factor – marine resource – to represent the marine area. Marine resource as the pre-dominant and sector-specific factor is the most important factor and limits the expansion of OWF production. Inclusion of these spatial conflicts results in more significant negative impacts on the seafood sectors. As expanding OWFs take up more marine resource, less would be available for the fishing sector, resulting in significant negative impacts on fishing output (-27.2%). However, in the real world the negative impacts may not be as significant as simulated in the model since it assumes mutually exclusive use of marine resource between OWFs and fishing while in reality fishermen would go elsewhere to continue fishing (Hooper et al., 2015; Gray et al., 2016).

The magnitude of negative impacts also depends on the use efficiency of marine resource. High use efficiency would have less negative impacts whereas low use efficiency would result in larger reductions in seafood productions. Significant reductions in domestic supply increase seafood prices and decreases the affordability of seafood to households. Since households are assumed to maximise utility, when the domestic seafood become less available and more expensive, they may either choose relatively cheaper imported fish or replace fish protein in their diet, which could reduce their food utilization as fish is considered to be high nutrition value and thus contributes to a healthy diet (FAO, 2018).

Although these conflicts with the expansion of OWFs arising from competition for limited economic and natural resources have negative impacts, seafood sectors could benefit from the closed area and artificial reef effect created by energy infrastructure (e.g. Langhamer, 2012; Maar et al., 2009; Reubens et al., 2013). Previous works confirms the existence of artificial reef effect but there is still lack of evidence whether fishermen could benefit from it economically. The results presented in Application 3 demonstrate that positive impacts on fish stocks due to closed areas and artificial reef can have significant economic effects by stimulating fishing production. The fish processing and the aquaculture sector increase their production, benefiting from increased fishing output. More importantly, such positive impacts could sufficiently offset the negative impacts on seafood production brought by OWF expansion, under the condition that the fishing sector can get access to the enhanced fish stock. These results confirm that potential economic synergies exist between OWFs and fishing activities from the economic perspective and complete the last piece in the nexus assessment.

5.1.2.3. Household distributional effects

The model is also used to examine distributional effects on household behaviours. In general, lower income households have less disposable income to spend so that they are more sensitive to price changes whereas the opposite happens to higher income households. Also, households in the different income brackets have different consumption patterns regarding different commodities. Lower income households are more sensitive to changes in price for electricity, which is a necessity good accounting for greater share of their total consumption. Conversely, higher income households tend to respond more to seafood price changes as they are more likely to consume seafood (which is a comparatively high-valued source of protein).

As mentioned before, previous CGE model applications to marine renewables have not include distributional effects on households (e.g. Allan et al., 2008, 2014; Graziano et al., 2017; Lecca et al., 2017). In Application 1, the higher cost of OWFs is equivalent to lower labour and capital productivity resulting in a decrease in household income and consequently an overall reduction in consumption and loss of welfare. Such results support the concerns that higher energy prices (resulting in part from policies aimed at supporting renewable energy technologies to reduce carbon emissions) create an extra burden for households (Advani et al., 2013; Teller-Elsberg et al., 2016). However, when the cost of OWFs is lower it could bring down the electricity price so households are not subject to higher energy bills. Cheaper electricity would bring more benefit to lower income households who are able to increase electricity consumption and thus gain welfare. This is also supported by the results in Application 2 and 3, which shows how the massive expansion of OWFs through subsidy would further reduce electricity prices, from which lower income households would benefit most.

Previous studies demonstrated that mid- to high-income household categories would bear the most significant impacts from fish price volatility (Hoagland et al., 2015; Jin et al., 2012). The SEMM in this thesis also gives similar results. The increased cost of seafood due to increased competition of marine resource with expanding OWFs has more impact on higher income households. Household HH4 (the second highest income group) losses most welfare as higher seafood prices resulted in lower seafood consumption than before. When seafood becomes cheaper, through benefits from closed area and artificial reef effects (Application 3), higher income households gain more welfare than lower income households.

In conclusion, with increasing output and decreasing price, OWFs are able to undercut the estimated price of electricity from gas plants, which has remained steady and is expected to rise slowly in the future (CCC, 2017). Therefore, expanding OWFs increase energy security through the reduction of GHG emissions, diversification of energy supply, and provision of domestically produced and cost-competitive electricity. Meanwhile, fish supply is negatively impacted through trade-offs in production factors and conflicts in use of marine resource with expanding OWFs. The potential synergies through artificial reef effect could bring benefit to the fishing sector and could be sufficient to mitigate the above negative impacts. As for household behaviours, lower-income households tend to gain welfare from cheaper electricity while high-income households lose welfare due to more expensive seafood. The above main findings of the model results could be illustrative to policy design regarding the balance between the development of OWFs to increase energy security, ensuring fish supply, and sustainable use of natural resources in the marine environment. The next section will discuss the model results implication for policy.

5.2. Policy implication

5.2.1. Nexus thinking

The FEW nexus focuses on decision-making in the face of interrelationships among the production and consumption of food, energy and water (Hoff, 2011). The purpose of the nexus thinking is that rather than just focusing on an individual element, decisions based on the nexus are likely to avoid trade-offs, take advantage of synergies, and optimise use of resources (Kurian, 2017; McCarl et al., 2017). Therefore, applying the nexus framework could better address the rapid development of OWFs and its impact on seafood productions, from an integrated perspective as opposed to individual sector’s improvements in isolation (Howarth and Monasterolo, 2016). Nexus thinking could improve resource allocation and management, and enhance policy integration to ensure both food and energy security (Albrecht et al., 2018). In addition, the integrity of ecosystem services in the nexus framework ensures sustainable use of marine resources while it also extends access to resources (Fürst et al., 2017).

In particular, in the case of Scotland, the Scottish Government has not considered the impacts of OWFs on seafood production from the nexus perspective. As reviewed in Chapter 2, the Scottish Government recognised potential negative economic impacts of OWFs on marine activities and broadly concluded that the impacts ranged from negligible to moderate, with no particular attention paid to other seafood sectors nor to households (Scottish Government, 2019g). Clearly, such assessment is not sufficient to provide comprehensive information on how the economy would respond to the changes necessary to meet the ambitious targets for future net-zero emissions. Under this circumstance, with the help of energy-food nexus thinking, decision-making could go beyond simply prioritising rapid development of offshore wind energy to achieve GHG emission reduction but would also be mindful of the potential trade-offs with the seafood sectors.

Trade-offs have been widely studied in the energy-food nexus on land where developing biofuels poses a threat to fish supply through linkages related to both production (i.e. competition for land and other production factors) and consumption (i.e. decreasing household income and thus dampening food demand) as reviewed in Section 2.1.4 (e.g. Arndt et al., 2012; Banse et al., 2010; Prieler et al., 2013; Ringler et al., 2016; Timilsina et al., 2011). Substantially expanding biofuel production to increase energy availability negatively impacts fish supply, which is similar to the marine-specific findings highlighted by this thesis. Technologies like offshore wind turbines require less land per unit of energy than other options such as biofuels produced from food and energy crops (Inger et al., 2009). However, macroeconomic and environmental linkages still connect marine renewable energies with food production in a similar way as biofuel and agriculture, especially in terms of conflicting use of marine areas with fishing activity, seafood production and the subsequent impacts on the wider economy. Scenario analyses using the CGE model, such as in this thesis, could alert policy makers to potential significant negative impacts on seafood sectors and enable them to compare the impacts of different actions on the macro-economy to support decision and thus indicate policy. Although this SEMM model cannot provide a forecast, the model results could serve as indications of the relative scale of effects and distribution of impacts under different scenarios.

Robust analytical nexus frameworks can enhance the provision of multi-sectoral nexus solutions, in the form of integrated policy, cohesive community decision-making, maximization of synergies, and sustainable outcomes achieved through socially and politically-feasible strategies (Albrecht et al., 2018). Although there is increasing number of studies focusing on nexus and nexus assessment, it is not yet widely adopted in either policy or development planning (Simpson and Jewitt, 2019; Wicaksono et al., 2017). The possible reason for not promoting nexus framework in actual policy decisions is that applying nexus framework is relatively challenging and costly, as sector-specific actions have to be balanced to optimize rather than maximize (Bhaduri et al., 2015). So far, only the conceptual understanding of nexus assessment has been be translated into policy intervention recommendations. For example, a nexus assessment of the Mekong basin recognised that significant growth in the capacity and supply of hydropower developments could reduce fish stocks and fish diversity, as well as the availability of water to downstream users (Smajgl et al., 2016).

The policy intervention was suggested that by managing energy demand, as opposed to purely focusing on energy supply and capacity alone, the negative impacts of hydropower on food and water security could be reduced (Smajgl et al., 2016).

By employing a nexus framework and making use of impact assessment in an advanced quantitative model, the SEMM results could provide robust evidence for policy interventions that consider both the increasing demand for OWFs and maintenance of seafood supply from the marine environment, which fit with policy maker's interests in identifying the magnitude of economic impacts (Scottish Government, 2019g). Potential negative nexus linkages are demonstrated in the SEMM results to alert the government to take actions to maintain seafood production. As long as OWFs are expanding, there will typically be negative impacts on the seafood sectors, mainly driven by the general equilibrium competition for limited marine resources. Although reductions in seafood production do not have profound effects across the economy as a whole, these effects may be locally or regionally significant, and fishing activities are still traditionally and culturally important for Scotland (Scottish Government, 2015). Possible mitigation policies include compensation for fishing businesses operating near planned OWFs areas or the creation of a common fund allowing fishermen to diversify (Alexander et al., 2013). The Oil and Gas UK Fishermen's Compensation Fund, which compensates for damages to fishing gear by oil and gas infrastructures, could set a precedent for similar funds for OWFs (BEIS, 2018b). Quantifying the negative economic implications on the fishing sector will help to determine the scale of funding required through such mitigation schemes. Meanwhile, potential positive nexus linkages are also assessed in the SEMM and indicate the necessity of marine spatial planning to coordinate the nexus, which will be discussed in Section 5.2.3.

5.2.2. Integrating natural capital and ecosystem services in nexus assessment

In determining the energy-food nexus, economic activities need ecosystem services to be involved in production as it is important to consider the trade-offs between economic benefits and degradation of natural capital to maintain long-term sustainability of resources (Bizikova et al., 2013; Hanes et al., 2018). Only focusing on the nexus impacts at an economic level is insufficient since increases in production benefiting from ecosystem services could be achieved from overexploiting natural capital (Guerry et al., 2015). Therefore, to avoid ecosystem service degradation and maintain productivity, integration of natural capital and ecosystem services in the energy-food nexus assessment is essential for informing sustainable development policy and decisions (Biggs et al., 2015), particularly in support of meeting targets of the SDGs.

Natural capital and ecosystem services approaches have been incorporated into policy and decision making in the UK (Hooper et al., 2019) and many other countries around the world (Guerry et al., 2015). For example, the Scottish Government has included natural capital assets as one of the National Indicators to track progress towards the achievement of ambitious outcomes (Scottish Government, 2018d). Within its' economic strategy, the Scottish Government has also stated its ambition to put natural capital at the heart of economic prosperity (Scottish Government, 2018d). As the creation of natural capital accounting raises the awareness of the importance of natural resources in economic terms, it needs further application with economy-wide modelling, such as CGE models, to exploit the economic-environmental interactions. It is more straightforward for stakeholders to see the role of natural capital in the economy by providing quantitative assessment of trade-offs between them (Ochuodho and Alavalapati, 2016). With an integrated framework, the nexus can be considered as a whole to avoid depletion of natural capital and achieve sustainability for ecosystem services and with better consideration of food and/or energy production (Hanes et al., 2018). Furthermore, an integrated model would partly resolve the problem of inconsistency between different model outputs and would offer a more cohesive story to the policy maker, even if it is only done at a very aggregate level (Brouwer et al., 2018).

As reviewed in Chapter 2, previous research has shown that the expansion of OWFs has mixed impacts on ecosystem services (Hooper et al., 2017; Papathanasopoulou et al., 2015), but the quantitative assessment is lacking. Using the integrated framework of natural capital and economy as proposed in this thesis could facilitate analysis assessing the impacts of certain policies and decisions on the sustainable use of natural capital and the provision of ecosystem services, simultaneously considering the different components of the energy-food nexus. This integrated model tries to help in designing a resource-efficient policy, which allows evaluation of the potential benefits of alternative options for resource allocation across economic sectors and environmental assets.

Application 3 demonstrates the feasibility of integrating the natural capital and ecosystem services approach into the nexus assessment, providing further insight into the environmental dimension of the nexus. Both the ecosystem service and natural capital are incorporated endogenously in the model so that the two-way interrelationship between economy and environment is built. Application 3 results explore economic impacts on natural capital stock (i.e. OWFs expansion reduces production of fishing and thus slightly increases the level of fish stock) and tracks how changes in natural capital interact with economic activity (i.e. the economy benefited slightly from increased fish stock near OWFs boundaries due to the closed area and artificial reef effect). Such results also imply the economic feasibility of co-location between fishing activity and OWFs, highlighting the possibilities for maximizing synergies in the nexus. Therefore, integrating the natural capital and ecosystem services approach in the nexus assessment extends the framework from the socioeconomic level to the environmental level, with the help of natural capital accounting.

Currently the framework in this work only covers provisioning ecosystem services, and quantitative impact assessment for other types of ecosystem services is still lacking, mainly due to data limitations (Hooper et al., 2019). There are 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). Although cultural ecosystem services are not included in the SEMM-Natural capital model, these monetary value enables the integration of cultural ecosystem services in a CGE model. Unlike provisioning ecosystem services, cultural ecosystem services are not normally used as direct production inputs in the economy. Instead, they 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 (e.g. Allan et al., 2018; Carbone and Smith, 2013). By placing monetary values on ecosystem services, environmental impacts of OWFs would be compared using the same units as economic and social impacts (Mangi, 2013).

As the marine environment is increasingly vulnerable to economic, social and environmental shifts (Austen et al., 2018), the energy-food nexus could help better coordinate the marine resource conflicts and make better use of synergies between

OWFs and seafood production. The model results in the thesis provide a useful starting point for characterizing and responding to risks to fish supply from seafood in the increasing use of marine areas from developing other marine activities, mainly offshore wind energy. Meanwhile, potential synergies between OWFs and fishing activities have also been highlighted by the model results, if these two could be better coordinated. As shown from land use management, the increase in biofuel demand should be accommodated with mechanisms like land allocation plans or restrictions on land substitution to avoid the conflict with agricultural production (Fürst et al., 2014; Timilsina et al., 2012), which provides insights for development of OWFs under an equivalent marine spatial planning framework.

5.2.3. Implications to marine spatial planning

One important implication of the quantitative assessment by the CGE model is that the relative importance of the connected sectors can be evaluated and outputs used to provide better information for marine spatial planning (MSP) and wider decision making (Douvere and Ehler, 2009).

The innovative marine resource allocation module developed in the SEMM (Application 2) has provided further evidence that negative economic impacts could be significant if no specific spatial plan is applied to avoid such conflict arising through exclusive use of marine areas. Furthermore, if the use efficiency of marine resource could be increased through better marine planning, the negative impacts on seafood sectors could be alleviated. Meanwhile, the potential synergies due to the closed area and artificial reef effect could bring positive impacts on seafood productions and help mitigate the negative impacts of OWFs expansion (Application 3). Nexus thinking of minimising trade-offs (i.e. avoiding exclusive use of marine areas) and maximising synergies (i.e. making use of the artificial reef effect and increasing marine resource use efficiency) should be taken into consideration in any planning framework. This supports previous findings from a combined spatial and economic model which suggested that careful spatial planning of OWFs may increase fish stocks and thus actually benefit fishing activity (Punt et al., 2009). Previous research has demonstrated the feasibility of co-location of OWFs with fishing or aquaculture from ecological (Hooper et al., 2015; Hooper and Austen, 2014; Langhamer and Wilhelmsson, 2009), geographical (Gimpel et al., 2015; Jongbloed et al., 2014; van den Burg et al., 2019), and social (de Groot et al., 2014; Stelzenmüller et al., 2016; Wever et al., 2015) perspectives. In practice, examples are found where fishing activities co-exist with OWFs in the UK (Gray et al., 2016), as not all fishing gears would be excluded from OWF areas. Fishing with mobile gear tends to be most impacted due to insufficient or inadequate space between turbines to deploy fishing gear (Mackinson et al., 2006) and significant safety concerns (Hooper et al., 2015). In comparison, static gear has the potential to be co-located with OWFs (Hooper and Austen, 2014). In addition, through the designation of safe shipping lanes through offshore wind arrays, spatial planning has the potential to avoid areas of larger impacts on fishing activity (Scottish Government, 2019b). There are further case studies implementing co-location of aquaculture and OWFs (e.g. Buck et al., 2004).

This co-location approach is also of potential use for wider marine ecosystem services as it can be used to compare all users of marine space. The impacts of OWFs on ecosystem services have been considered by Hooper et al. (2017). For regulating services, increase in mussel has been observed that is likely to increase the capacity of the system for waste remediation and also 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 co-location policy. For supporting services, studies have shown positive effects for fish and benthic species and communities, including an increase in the biodiversity around turbine foundations (Inger et al., 2009). The co-location will allow maximization of synergies between competing uses to be made more easily in the decision context of interest and in terms of human wellbeing. SEMM makes the attempt to integrate natural capital and ecosystem services with CGE models, so that policy makers can examine how OWFs will impact social and economic factors, but also how the environmental impacts will affect these social and economic factors. However, due to the high natural variability of marine systems and the current monitoring technology, quantifying some of the impacts on ecosystem services is still limited and thus transforming them into CGE model is not accessible yet. But once these data are available, quantifying the potential benefit of the co-location will be achievable.

While co-location is emerging as a potential means to tackle marine resource trade-offs between OWFs and fishing activities, it can be difficult to implement in practice, with success dependent on stakeholder attitudes and developer co-operation (Christie et al., 2014). The establishment of co-location would need appropriate methods of assessing fishing effort displacement by OWFs, appropriate legal and insurance frameworks, and careful design of the location since the extent is site-specific (Christie et al., 2014; de Groot et al., 2014). However, the challenges of effective MSP are recognised and decision makers require guidance on how to zone the ocean for multiple uses in a way that achieves both ecological and socioeconomic goals (Yates et al., 2015). There is still a learning process required in MSP before this co-location idea is successfully implemented (Smith and Jentoft, 2017).

In terms of specific policy implications for Scotland, a National Marine Plan (NMP) has been published aiming to assist in managing increasing demand for the use of Scotland's marine environment, which highlights the importance of supporting economically productive activities sustainably and to address the interactions with each other (Scottish Government, 2018e, 2015). Both marine renewable energy and seafood production are highlighted for their significant role in Scotland's marine economy (Scottish Government, 2019d). A social and economic impact assessment of the sectoral marine plan for offshore wind energy, conducted as part of the NMP, provided a list of potential socioeconomic consequences of interactions between OWFs with commercial fisheries (Scottish Government, 2018b). However, no quantitative assessment has been provided so far. The results of this thesis fill this gap by measuring the trade-offs from a macroeconomic perspective and show that OWFs expansion will take marine resources away from fishing activity and thus reduce the contribution of the seafood sector to Scotland's economy. This provides further weight to the argument that specific marine policies are required. Although the displacement of fishing activity due to interactions with OWFs and the potential of co-location have been recognised in Scotland's NMP, there are currently no specific measures to reduce trade-offs or enhance synergies. Considering the increasing demand for renewable energies in Scotland, it is therefore necessary to have specific MSP regarding the nexus linkages between marine renewables and seafood production.

5.2.4. Implications for other marine renewables

The SEMM could be applied on other marine renewables to make assessment. If economic changes are occurring to address climate change, there will need to be economic analysis to measure the magnitude of such changes and the potential impacts on the economy. This would help to better support important sectors (such as the renewable or seafood sectors) in the transition.

Scotland has ambitious targets to reach 100% of its electricity to be generated from renewable energy by 2020 and has a very positive perception of the potential for all forms of marine renewable energy technologies (Scottish Government, 2019g). It is estimated that Scottish waters have the potential to generate around 10% of Europe's wave power and possess 25% of the potential European offshore wind and tidal resource, and have almost 40% of the total UK resource (Scottish Government, 2011). For wave and tidal energy, the availability of energy resources equates to an installed capacity of around 12 – 20 GW (BEIS, 2013). Unlike offshore wind energy, the costs of wave and energy technology are still high and they are only slowly progressing to commercialisation (Neill et al., 2017). The Chapter 4 Application 1 results show that support from the CfD scheme is sufficient to stimulate the production of high cost renewable energies but not sufficient enough to make household benefit from slightly lower electricity price as households have decreasing income. It is only when the cost has been brought down that renewable energy has the potential to increase energy security by increasing both availability and affordability. However, the CfD scheme is necessary to be applied to floating OWFs, wave and tidal energy when their costs are still higher than average electricity generation cost. The reason is that the increased deployment through CfD scheme promotion leads to learning-by-doing and learning-by-research, which have a significant effect on the cost reduction trend of new energy source technologies (e.g. Dalton et al., 2015; Lecca et al., 2017). In this light, the key results for OWFs provide a rough guide as to what ramifications can be expected from developing marine renewables for Scotland at the macro level.

It can be argued that as OWFs have joined onshore wind and solar in becoming subsidy-free renewable energy, there is no need for new renewables sectors to be subsidised, especially where reducing energy poverty is a stated government aim (BEIS, 2015, 2019). However, it is important to continue expanding other marine renewable technologies even if their costs are still higher. Increasing the diversity of energy sources enhances energy security. Developing marine renewable energy technologies can enable a country to establish high levels of domestic control over the energy supply chain (Valentine, 2011). With more diverse domestic energy technologies, energy resilience and the stability of the electricity system in the event of an accident (e.g. a war) are increased, and thus energy security is higher (Sovacool, 2013). Therefore, maximization of domestically produced energy supply is the most secure way to minimize energy supply risk and increase energy security (Bang, 2010). Furthermore, developing renewable energies would bring economic benefit through exporting the surplus electricity, if the cost of other marine renewable energy reduces (as shown in Application 1 Scenario 2). With demand in Scotland not expected to exceed 5.7 GW by 2040 (Scottish Government, 2019b), it could be feasible to export electricity and get benefit.

Although developing a diverse energy supply would increase energy security, the subsidisation of high-cost renewables is still under debate. Where the subsidy encourages effective development of renewables to become mature technologies offering significant benefits for electricity supply diversity and industry creation, then the subsidy could be considered as an investment generating future returns from the export of technology and intellectual property (Andersson et al., 2017; Jeffrey et al., 2013). Furthermore, subsidy might provide an incentive for investments to improve the local content in OWFs supply chains, which would bring greater economic benefits (Gilmartin and Allan, 2015; Graziano et al., 2017). Conversely, although renewable energies become cheaper due to subsidies and learning-by-doing, they are not perfect substitutes for conventional energy. Moreover, fossil fuel price would decrease as demand initially fell so that it would eventually become competitive in the energy market (Kalkuhl et al., 2013).

The results from the sensitivity analysis in Application 1 highlight the importance of substitution of OWFs and this also applies to other offshore renewables. The renewable energy share in overall electricity generation depends to a degree on the elasticity of substitution between the renewable and conventional electricity generation. When the renewable energy still has high production cost, a subsidy could help increase its share in total electricity generation but even with high substitution values will only make slow progress. In comparison, sensitivity analysis results where renewables have low production cost demonstrate that the greater replacement of other conventional electricity with renewable energy implies a more rapid move towards low-carbon generation. The strong substitution relationship might become more feasible as innovation widens the range of technological possibilities, such as improvements in storage (Acemoglu et al., 2012). If high substitution is achievable, from the macroeconomic perspective, renewable energy targets to support net-zero goals will become more easily attainable.

5.3. Limitations and Future Research

In this thesis, a static CGE model (SEMM) has been developed to assess the trade-offs between OWFs and seafood productions. The SEMM integrates economic, social and environmental components of the nexus in one framework by utilizing a module extension design that considers spatial conflict, while also integrating natural capital in a way that is flexible and able to accommodate new environmental inputs and outputs.

The SEMM developed in this thesis inevitably still suffers from some limitations in terms of assumptions and simplifications made in the modelling framework. CGE models have a number of restrictive assumptions to control the size and reflect the aim(s) of the model (Burfisher, 2017). The main criticism of these assumptions is that the model results depend on the estimation of exogenous parameters in functional forms, mainly elasticities. The elasticities are estimated based on the reference year data, which means that the parameter estimations may be sensitive to the choice of reference year and thus the results are relative to reference data as well (Burfisher, 2017). The model results therefore depend on the elasticity estimations assumed in the model. However, sensitivity analysis is efficient to test the robustness of the results which could partly overcome the uncertainty of elasticities, e.g. sensitivity analysis in Application 1 and 2. Furthermore, the model is static and so lacks a temporal dimension. Fixed production factor supply and full employment are often assumed in static CGE models, which may overestimate the impacts of OWFs expansion due to limited factor availability.

Modelling generally uses simplifications due to data limitation and model size control so that these simplifications are always under criticism. First, there is no differentiation of fishing types, only information on the overall impact on fishing activity is given whilst different fishing gears respond differently to OWFs (Bartelings et al., 2015). Then, the assumption in Application 2 that fishing grounds would be evenly distributed across the sea is an example of such a simplistic choice. In particular, climate change is pushing fish distribution further north (Perry et al., 2005) and the overlap between OWFs and fisheries may change. Next, restricted by the static CGE structure, the choice of function linking harvest fish and fish stock in Application 3 is a linear relationship from a classic fish harvest function which lacks the population dynamics of fish. Furthermore, only one type of ecosystem service (i.e. harvest fish as provisioning service) and one aspect of natural capital (i.e. fish stock as natural capital asset) are included in the model. Whether offshore wind production and use can have a negative or positive impact on other marine ecosystem services depends on the specific type of ecosystem services (Hooper et al., 2017). The inclusion of only one type of fish is also a simplification considering that different fish have different market value.

There are options for further work to improve the CGE model structure and overcome the simplified assumptions. First, the static CGE model could be developed into a recursive dynamic model by sequentially solving a static model following a time path (Burfisher, 2017). In the recursive dynamic model capital stock or population growth functions could be added to the model exogenously to relax the fixed factor supply assumption (e.g. Thurlow, 2008). In particular, a dynamic CGE model could be more coherent with fish population dynamics (e.g. Finnoff and Tschirhart, 2008), which better describe the changes in fish stock. The results from the dynamic model could provide policy makers with useful insights regarding long-run sustainability of fish as natural capital and the sustainable economic well-being of fishing communities (Waters and Seung, 2010). Then, if the data is available, the fishing sector could be further differentiated by different fishing gear types, different fish stocks, or different fishing effort, by adding additional accounts to the SAM. For example, if disaggregated by gear types, the SAM has to create corresponding row and column activity accounts for certain fishing gear types (e.g. Pan et al., 2007). To better illustrate the impact of further north distributed fish due to climate change, the SAM would need to be disaggregated into different regions to distinguish different fishing effort distribution (e.g. Wang et al., 2020). Last, there is still a gap for modelling feedback effects between the economy and the environment. Various ecosystem services and natural capitals should be integrated into the CGE model. With advancement and convergence of methodologies in natural capital accounting and valuing ecosystem services, more natural capital and ecosystem services could be accounted in the economy and incorporated in CGE models as production inputs or consumption goods (Allan et al., 2018).

6. Conclusion

This thesis quantitatively evaluates the macroeconomic impacts of offshore wind farms (OWFs) on seafood production and the wider economy from the energy-food nexus perspective. Through the indirect macroeconomic linkages, OWFs have impacts on seafood production costs due to the competition on the use of limited production factors. Through the direct environmental linkages, development of OWFs would cause conflicts with fishing activities due to displacement of fishing activities and loss of fishing grounds due to fishermen's inability or reluctance to fish within OWF areas. Meanwhile, fishing activities may benefit from increased fish stock as OWFs could function as artificial reefs to attract, and potentially increase the production of fish. The fishing activities further influence the seafood production sectors through the macroeconomic linkages. The energy-food nexus thinking could help avoid the conflicts and benefit from the synergies between OWFs and seafood production. Furthermore, the environmental impacts on fish stock could be interpreted using a natural capital and ecosystem services approach which helps better inform policy decisions on sustainable use of resources.

There are three main objectives of this thesis. The first is to develop a macroeconomic framework to analyse the nexus linkage between OWFs and seafood production. A static Scottish Economy Marine Model (SEMM) has been built to assess the impacts from a macroeconomic perspective. The case study chooses Scotland where OWFs are under rapid development while seafood production has cultural, traditional and economic importance. In particular, to better highlight the trade-offs between OWFs and specific elements of seafood production, the OWF electricity and the three seafood sectors have been disaggregated in the model structure. It enables the model to assess the sectoral impacts on OWF electricity and seafood production to emphasise their availability as nexus elements. Households are also divided into five groups based on income levels to analyse the distributional effects, so that the model could assess the affordability of nexus elements. The model structure is developed in three steps starting with a purely economic assessment, then including an innovative marine resource allocation module to better describe the spatial conflicts, and finally integrating the environment as a new sector to own natural capital and provide ecosystem services as production inputs. The marine resource allocation module virtualises the spatial conflict between OWFs and fishing activities to allow the quantitative assessment of the macroeconomic impacts of the replacement of fishing grounds. Integrating natural capital and ecosystem services into CGE model enables a comprehensive analysis of the two-way linkage between the economy and natural environment. The improvements in the methodological framework cover all three dimensions of sustainability (i.e. economic, environmental and social) in the nexus approach.

The second objective of this thesis is to assess the economic and environmental linkages between offshore wind energy and seafood production. Based on the three stages of model development, there are three applications of the CGE model. The first one uses the basic structure of SEMM to compare the near-term, indirect impact of decreasing cost of OWFs through economic linkages and assess the direct impact of displacement of fisheries on seafood sectors. The high cost of OWFs shows a costly way to develop renewable energies through subsidy scheme as neither the households nor the GDP would benefit. The falling cost of electricity from OWFs would have a positive impact on the economy overall and benefit lower income households, contributing to the reduction in fuel poverty. The results suggest that increasing the number of OWFs would generally have a negative but limited effect on seafood production sectors. The direct impact of displacement of fisheries are negative but are limited and largely confined to three seafood sectors. Therefore it is necessary to assess the direct environmental linkages. The second application therefore creates a novel marine resource allocation module within the SEMM to better assess the trade-offs between expanding OWFs and fishing activities. It firstly compares the results with and without marine resource allocation module and the results shows substantial differences. The increasing OWFs results in more significant negative impacts on seafood supply and therefore fish supply since marine resource is taken by expanding OWFs, compared to no marine resource allocation. It then compares the different use efficiency of marine resource to highlight that increasing efficiency would help alleviate the negative impacts on seafood sectors. At this stage, no synergies has been included in the nexus assessment. The third application integrates natural capital into the CGE model, using fish stock as an example of natural capital, to evaluate the impacts on fishing not only at an economic level but also at an environmental level. As the previous two application results indicate, expanding OWFs leads to negative impacts on fishing production, however, the fish stock increases slightly due to less fish being harvested. Meanwhile, the small increase in fish stock due to the artificial reef effect would bring benefits largely confined to seafood productions and minor impacts to the rest of economy.

The last objective of this thesis is the policy implications of the model results. The SEMM developed in the thesis fills the gap of quantitative impact assessment of offshore wind energy on seafood production from the nexus perspective. The results in this thesis suggest substantial trade-offs between expanding OWFs on seafood production, through both macroeconomic and environmental linkages. Integrating the natural capital and ecosystem services approach in the modelling framework highlights the potential synergies (i.e. increased fish stock due to artificial reef effect) that the seafood sectors could benefit from the nexus perspective. It also provides a straightforward way for stakeholders to see the role of natural resources in the economy. These results are robust evidence for policy interventions that demonstrates the benefits of using nexus thinking to minimise trade-offs and maximise synergies, covering both the increasing energy security by OWFs and maintenance of seafood supply from the marine environment. One potential policy intervention is marine spatial planning (MSP), where co-location of the OWFs and fishing activities could avoid exclusive use of marine areas (trade-offs) and benefit from increased fish stocks (synergies). Furthermore, the methodology and modelling tool developed in this thesis are also applicable to other marine renewables such as wave and tidal energy, the development of which should also apply the nexus thinking to consider their impacts on the seafood production and the wider economy.

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Appendix 1 – Mathematical specification of the CGE model

The following tables provide a complete listing of SEMM's indices, parameters, variables and equations. The ordering of parameters and equations follows the description of the SEMM found in Section 3.2 of this thesis.

Table A1 Model indices, variables and parameters

Indices			
a	Production activity (8 activities in total)	c	Commodity (7 commodities in total)
f	Factors (labour, capital, marine resources)	h	Household (5 households quintiles)
Exogenous parameters (Greek characters)			
α_a^a	Production function shift parameter	δ_a^a	Production function share parameter
$\alpha_{a\,c}^{ac}$	Domestic commodity aggregation function shift parameter	$\delta_{a\,c}^{ac}$	Domestic commodity aggregation function share parameter
α_a^{va}	Value added function shift parameter	δ_{La}^{va}	Value added function share parameter
α_c^q	Import function shift parameter	δ_c^q	Import function share parameter
α_c^t	Export function shift parameter	δ_c^t	Export function share parameter
$\gamma_{c,h}$	Subsistence requirement on commodity	$e_{c,h}$	Household marginal budget share
ρ_a[8]	Production function exponent	ρ_c^{ac}	Domestic commodity aggregation function exponent
ρ_a^t	Export function exponent	ρ_a^{va}	Value added function exponent
φ	Frisch parameter	ρ_a^q	Import function exponent
Extended model structure – Section 3.2.2			
ρ_{marine}^a	CES activity function exponent	δ_{marine}^{va}	share parameter of marine resources
α_a^{kl}	Capital-labour composite shift parameter	δ_{La}^{kl}	Capital-labour composite share parameter
ρ_a^{kl}	Capital-labour composite function exponent	$\theta_{a\,c}$	Yield of output c per unit of activity a
Extended model structure – Section 3.2.3			
α_a^{nk}	Natural capital function shift parameter	α_a^{na}	Harvest fish share parameter

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[8] For CES functions, $\sigma = \frac{1}{1+\rho}$, where σ is the elasticity of substitution and the ρ is the exponent.

Table A1 continued: Model indices, variables and parameters

Exogenous parameters (Latin characters)			
$ica_{c\,a}$	Intermediate input coefficients	sax_{ac}	Yield of output c per unit of activity a
$cwts_c$	Consumer price index parameter	ti_{cor}	Tax rate for corporation
mps	Marginal propensity to save	ta_a	Tax rate for production activity
pwm	World import price	ti_h	Tax rate for household
pwe	World export price	$transfr_{cor\,gov}$	Transfer from government to corporation
$qinv$	Base investment demand quantity	$transfr_{cor\,h}$	Transfer from household to corporation
$shif_{cor\,k}$	Share of capital endowment to corporations	$transfr_{cor\,row}$	Transfer from rest of the world (RoW) to corporation
$shif_{gov\,k}$	Share of capital endowment to government	$transfr_{gov\,row}$	Transfer from RoW to government
$shif_{h\,k}$	Share of capital endowment to households	$transfr_{h\,cor}$	Transfer from corporation to households
$shif_{h\,l}$	Share of labour endowment to households	$transfr_{h\,row}$	Transfer from RoW to households
$shrg_c$	Share of government consumption	$transfr_{row\,cor}$	Transfer from corporation to RoW
$shr_{cor\,h}$	Share of households transfer to corporation	$transfr_{row\,gov}$	Transfer from government to RoW
Endogenous variables			
$CORSAV$	Corporation saving	QG_c	Government consumption quantity
CPI	Consumer price index	$QH_{c,h}$	Household consumption quantity
EG	Government total consumption	$QINV_c$	Investment demand quantity
EH_h	Household total consumption	$QINT_{c\,a}$	Input from composite commodity c to produce activity a
EXR	Exchange rate	$QINTA_a$	Aggregate intermediate input quantity
$FSAV$	Foreign saving	QKD_a	Capital demand quantity

Table A1 continued: Model indices, variables and parameters

Endogenous variables			
EXR	Exchange rate	$QINTA_a$	Aggregate intermediate input quantity
$FSAV$	Foreign saving	QKD_a	Capital demand quantity
GDP	Gross domestic product	QKS	Capital supply quantity
$GSAV$	Government saving	QLD_a	Labour demand quantity
$IADJ$	Investment demand adjustment factor	QLS	Labour supply quantity
PA_a	Activity output price	QM_c	Import quantity quantity
PD_c	Domestic supply price	QQ_c	Composite supply quantity
PE_c	Export price	QVA_a	Composite value-added quantity
$PGDP$	Price of GDP	QX_c	Aggregate commodity quantity
PM_c	Import price	$QXAC_{a\,c}$	Marketed output quantity of commodity c from activity a
$PINTA_a$	Aggregate intermediate input price	$TABS$	Total absorption
PQ_c	Composite commodity price	WK	Economy-wide capital rent
PX_c	Aggregate producer price for commodity	$WKDIST_a$	Sector distortion in capital rent
$PXAC_{a\,c}$	Producer price of commodity c for activity a	WL	Economy-wide labour wage
PVA_a	Composite value-added price	$WLDIST_a$	Sector distortion in labor wage
QA_a	Activity output quantity	$YCOR$	Corporation income
QD_c	Domestic supply quantity	YG	Total government revenues
QE_c	Export quantity	YH_h	Total household income
Extended model structure – Section 3.2.2			
$QKLD_a$	Quantity of capital and labour composite	$PKLD_a$	Price of capital and labour composite
$WMRDIST_a$	Sector distortion in marine resource price	$WMRD$	Economy-wide marine resource price
$QMRD_a$	Marine resource demand	$QMRS$	Total marine resource supply

Table A1 continued: Model indices, variables and parameters

Endogenous variables

Extended model structure – Section 3.2.3

B	Total fish stock	WNK	Economy-wide natural capital price
$QENV_a$	Quantity of harvest fish	$WNKDIST_a$	Sector distortion in natural capital price
$EENV$	The rest of fish stock	WPK	Economy-wide physical capital price
$QNKD_a$	Quantity of ecosystem service (=harvest fish)	$WPKDIST_a$	Sector distortion in physical capital price
$QPKD_a$	Quantity of physical capital		

Table A2 SEMM equations

Equations	Variables
Production	
1. $QA_a = \alpha_a^a \times [\delta_a^a QVA_a^{\rho_a} + (1-\delta_a^a) QINTA_a^{\rho_a}]^{\frac{1}{\rho_a}}$	QA_a QVA_a $QINTA_a$
2. $\frac{PVA_a}{PINTA_a} = \frac{\delta_a^a}{1-\delta_a^a} (\frac{QINTA_a}{QVA_a})^{1-\rho_a}$	PVA_a $PINTA_a$
3. $PA_a \times QA_a = (1+ta_a) \times (PVA_a \times QVA_a + PINTA_a \times QINTA_a)$	PA_a
4. $QVA_a = \alpha_a^{va} \times [\delta_{La}^{va} QLD_a^{\rho_a^{va}} + (1-\delta_{La}^{va}) QKD_a^{\rho_a^{va}}]^{\frac{1}{\rho_a^{va}}}$	QLD_a QKD_a
5. $\frac{WL \times WLDIST_a}{WK \times WKDIST_a} = \frac{\delta_{La}^{va}}{1-\delta_{La}^{va}} (\frac{QKD_a}{QLD_a})^{1-\rho_a^{va}}$	WL $WLDIST_a$ $WKDIST_a$ WK
6. $PVA_a \times QVA_a = WLDIST_a \times WL \times QLD_a + WKDIST_a \times WK \times QKD_a$	n.a.
7. $QINT_{c\,a} = ica_{c\,a} \times QINTA_a$	$QINT_{c\,a}$
8. $PINTA_a = \sum_{a \in A} ica_{c\,a} \times PQ_c$	PQ_c
Composite commodity	
9. $PA_a = \sum_{c \in C} PXAC_{a\,c} \times \theta_{a\,c}$	$PXAC_{a\,c}$
10. $QXAC_{a\,c} = \theta_{a\,c} \times QA_a$	$QXAC_{a\,c}$

Table A2 continued: SEMM equations

Equations	Variables
Composite commodity	
11. $QX_c = \alpha_c^{ac} \times (\sum_{a \in A} \delta_{a\,c}^{ac} \times QXAC_{a\,c}^{-\rho_c^{ac}})^{-\frac{1}{\rho_c^{ac}}}$	QX_c
12. $PXAC_{a\,c} = PX_c \times QX_c \times (\sum_{a \in A'} \delta_{a\,c}^{ac} \times QXAC_{a\,c}^{-\rho_c^{ac}})^{-1} \times \delta_{a\,c}^{ac} \times QXAC_{a\,c}^{-\rho_c^{ac}-1}$	PX_c
13. $QA_a = \sum_c sax_{ac} \times QX_c$	n.a.
14. $QX_c \times PX_c = \sum_c (sax_{ac} \times QA_a \times PA_a)$	n.a.
Trade	
15. $QX_c = \alpha_c^t \times [\delta_c^t QD_c^{\rho_c^t} + (1 - \delta_c^t) QE_c^{\rho_c^t}]^{\frac{1}{\rho_c^t}}$	QD_c QE_c
16. $\frac{PD_c}{PE_c} = \frac{\delta_c^t}{(1-\delta_c^t)} (\frac{QE_c}{QD_c})^{1-\rho_c^t}$	PD_c PE_c
17. $PX_c \times QX_c = PD_c \times QD_c + PE_c \times QE_c$	n.a.
18. $PE_c = pwe_c \times EXR$	EXR
19. $QQ_c = \alpha_c^q \times [\delta_c^q QD_c^{\rho_c^q} + (1 - \delta_c^q) QM_c^{\rho_c^q}]^{\frac{1}{\rho_c^q}}$	QQ_c QM_c
20. $\frac{PD_c}{PM_c} = \frac{\delta_c^q}{(1-\delta_c^q)} (\frac{QM_c}{QD_c})^{1-\rho_c^q}$	PM_c
21. $PQ_c \times QQ_c = PD_c \times QD_c + PM_c \times QM_c$	n.a.
22. $PM_c = pwm_c \times EXR$	n.a.
Incomes and expenditures	
23. $YH_h = shif_{h\,l} \times WL \times QLD_a \times WLDIST_a + shif_{h\,k} \times WK \times QKD_a \times + transfr_{h\,gov} + transfr_{h\,cor} + transfr_{h\,row} \times EXR$	YH_h
24. $EH_h = (1 - MPS_h) \times (1 - ti_h) \times YH_h$	EH_h
25. $PQ_c \times QH_{c,h} = PQ_c \times \gamma_{c,h} + \beta_{c,h}(EH_h - \sum_{h \in H, c \in C} PQ_c \times \gamma_{c,h})$	$QH_{c,h}$
26. $YG = \sum_a \left(\frac{ta_a}{1+ta_a} \times PA_a \times QA_a\right) + \sum_h ti_h \times YH_h + ti_{cor} \times YCOR + \sum_c (tm_c \times pwm_c \times QM_c \times EXR) + \sum_a shif_{gov\,k} \times WK \times WKDIST(a) \times QKS + \sum_a WLAD \times QLAD(a) \times WLADIST(a) + govinv + transfr_{gov\,row} \times EXR$	YG
27. $PQ_c \times QG_c = shrg_c \times (EG - \sum_h transfr_{h\,g} - transfr_{cor\,g} - transfr_{row\,gov})$	QG_c EG
28. $QINV_c = IADJ \times qbarinv_c$	$QINV_c$ $IADJ$
29. $YCOR = shif_{cor\,k} \times WK \times QKS + transfr_{cor\,h} + transfr_{cor\,gov} + transfr_{cor\,row} \times EXR$	$YCOR$
30. $CORSAV = YCOR \times (1 - ti_{cor}) - \sum_h transfr_{h\,cor} - transfr_{row\,cor}$	$CORSAV$

Table A2 continued: SEMM equations

Equilibrium conditions	
31. $QQ_c = \sum_a QINT_{ca} + \sum_h QH_{c\,h} + QINV_c + QG_c$	n.a.
32. $\sum QLD_a = QLS$	QKS
33. $\sum QKD_a = QKS$	QLS
34. $EG = YG - GSAV$	$GSAV$
35. $\sum_c pwm_c \times QM_c + \sum_h transfr_{row\,h} + transfr_{row\,cor} + transfr_{row\,gov} + finv = \sum_c pwe_c \times QE_c + \sum_h transfr_{h\,row} + transfr_{cor\,row} + transfr_{gov\,row} + FSAV$	$FSAV$
36. $\sum_c (PQ_c \times QINV_c) + govinv0 + finv0 * EXR = \sum_h MPS_h \times (1 - ti_h) \times YH_h + CORSAV + GSAV + EXR \times FSAV$	n.a.
Macroeconomic variables	
37. $GDP = \sum_{c \in C} (QH_c + QINV_c + QG_c + QE_c - QM_c)$	GDP
38. $PGDP \times GDP = \sum_{c \in C} PQ_c \times (QH_c + QINV_c + QG_c) + \sum_{c \in C} PE_c \times QE_c - \sum_{c \in C} PM_c \times QM_c$	$PGDP$
39. $CPI = \sum_{c \in C} PQ_c \times cwts_c$	CPI
40. $TABS = \sum_{h \in H} \sum_{c \in C} PQ_c \times QH_{c,h} + \sum_{c \in C} PQ_c \times QG_c + \sum_{c \in C} PQ_c \times QINV_c$	$TABS$
Household welfare	
41. $EV = [u(QH1) - u(QH0)] \times \sum_{j=1} (\frac{p_j^0}{\beta_j})^{\beta_j}$	EV
42. $u(QH) = \sum_{j=1} (QH - \gamma_{c,h})^{\beta_j}$	n.a.
Extended model structure – Section 3.2.3	
43. $QVA_a = \alpha_a^{va} \times [\delta_{marine}^{va} QMRD_a^{\rho_a^{va}} + (1 - \delta_{marine}^{va}) QKLD_a^{\rho_a^{va}}]^{\frac{1}{\rho_a^{va}}}$	$QMRD_a$ $QKLD_a$
43.1 No marine resource: $QVA_a = QKLD_a + QMRD_a$	n.a.
44. $\frac{WMRD \times WMRDIST_a}{PKLD_a} = \frac{\delta_{marine}^{va}}{1 - \delta_{marine}^{va}} (\frac{QKLD_a}{QMRD_a})^{1 - \rho_a^{va}}$	$WMRDIST_a$ $WLAD$ $PKLD_a$
44.1 No marine resource: $PVA_a = PKLD_a + WMR \times WMRDIST_a$	n.a.
45. $PVA_a \times QVA_a = WMRD \times WMRDIST_a \times QMRD_a + PKLD_a \times QKLD_a$	n.a.
46. $QKLD_a = \alpha_a^{kl} \times [\delta_{La}^{kl} QLD_a^{\rho_a^{kl}} + (1 - \delta_{La}^{kl}) QKD_a^{\rho_a^{kl}}]^{\frac{1}{\rho_a^{kl}}}$	QLD_a QKD_a
47. $\frac{WL \times WLDIST_a}{WK \times WKDIST_a} = \frac{\delta_{La}^{kl}}{1 - \delta_{La}^{kl}} (\frac{QKD_a}{QLD_a})^{1 - \rho_a^{kl}}$	WL, WK $WLDIST_a$ $WKDIST_a$
48. $PKLD_a \times QKLD_a = WLDIST_a \times WL \times QLD_a + WKDIST_a \times WK \times QKD_a$	n.a.
49. $\sum QMRD_a = QMRS$	$QMRS$

Table A2 continued: SEMM equations

Equations	Variables
Extended model structure – Section 3.2.3	
50. $QVA_a = (\alpha_a^{va} + \alpha_a^{na} \times \alpha_a^{nk}) \times [\delta_L^{va} QLD_a^{\rho_a^{va}} + (1 - \delta_L^{va}) QPKD_a^{\rho_a^{va}}]^{\frac{1}{\rho_a^{va}}}$	$QPKD_a$
51. $\frac{WL \times WLDIST_a}{WPK \times WPKDIST_a} = \frac{\delta_L^{va}}{1-\delta_L^{va}} \left(\frac{QPKD_a}{QLD_a}\right)^{1-\rho_a^{va}}$	WPK $WPKDIST_a$
52. $PVA_a \times QVA_a = WL \times WLDIST_a \times QLD_a + WPK \times WPKDIST_a \times QKD_a + WNK \times WNKDIST_a \times QNKD_a$	$QNKD_a$ WNK $WNKDIST_a$
53. $QNKD_a = \alpha_a^{na} \times \alpha_a^{nk} \times \left[\delta_L^{va} QLD_a^{\rho_a^{va}} + (1 - \delta_L^{va}) QKD_a^{\rho_a^{va}}\right]^{\frac{1}{\rho_a^{va}}}$	n.a.
54. $QA_a = \sum_c sax_{ac} \times QX_c + QENV_a$	n.a.
55. $PX_c \times QX_c = \sum_a (sax_{ac} \times PA_a - QENV_a \times WNK \times WNKDIST_a)$	n.a.
56. $QENV_a = QNKD_a + EENV$	$QENV_a$ $EENV$
57. $B = B_0 + \left[r \times B_0 \times \left(1 - \frac{B_0}{k}\right)\right] - \sum_a QENV_a$	B

Appendix 2 – Examples of calibration of share and scale parameters

The calibration of this CGE model followed the instruction from Chapter 5 in Hosoe et al. (2010) and Appendix B in Löfgren et al., (2002). Here is one example of the calibration of share and shift parameter of CES function. Based on Equation 1 in Table A2, the SAM table could provide the initial value of QA_a, QVA_a, and $QINTA_a$. With the elasticity value obtained from previous work, the calibration of share and scale parameters is shown as below mathematic equations:

For share parameter: $\delta_a^q = \frac{PVA_a \times QVA_a^{1-\rho_a}}{PVA_a \times QVA_a^{1-\rho_a} + PINTA_a \times QINTA_a^{1-\rho_a}}$

For shift parameter: $\alpha_a^q = \frac{QA_a}{[\delta_a^q QVA_a^{\rho_a} + (1-\delta_a^q) QINTA_a^{\rho_a}]^{\frac{1}{\rho_a}}}$