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# Energy-food nexus in the marine environment: A macroeconomic analysis on offshore wind energy and seafood production in Scotland

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1 **Energy-food nexus in the marine environment: a macroeconomic analysis on offshore**  
2 **wind energy and seafood production in Scotland**

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1 **Highlight**

- 2 • A marine computable general equilibrium (CGE) model is developed with disaggregated
- 3 seafood and offshore wind energy sectors
- 4 • Subsidising the high production cost of offshore wind farms (OWFs) could stimulate their
- 5 production levels but would not benefit the economy
- 6 • Low-cost OWFs would increase both energy security and GDP
- 7 • Limited negative impacts are identified on seafood sectors by the expansion of OWFs

8 **Abstract**

9 The rapid development of offshore wind farms (OWFs) has stimulated debate about its overall  
10 socioeconomic impacts. Expanding the scale of OWFs increases the availability and affordability of  
11 electricity but could displace existing fishing activities and reduce food supply. To evaluate these  
12 impacts from a macroeconomic perspective, a computable general equilibrium (CGE) model is  
13 developed, using Scotland as a case study. A particular focus is placed on the disaggregated electricity  
14 and seafood sectors, their interconnectedness from an energy-food nexus perspective, and the  
15 distributional effects across household groups. This paper explores the trade-offs in the energy-food  
16 nexus between expanding OWFs and seafood sectors, and their impacts on food and energy security  
17 from macroeconomic perspective. The results suggest that increasing the number of OWFs would have  
18 a negative, but limited, effect on seafood production sectors through economic linkages. However, the  
19 falling cost of electricity from OWFs would have a positive impact on the economy overall and benefit  
20 lower income households, contributing to a reduction in fuel poverty. The model results raise the  
21 awareness of nexus linkages between OWFs and seafood production and are applicable to policies  
22 involving the development of other offshore renewables.

23 **Keywords** Energy-food nexus; Offshore wind energy; Computable general equilibrium model; Fuel  
24 poverty.

## 1 1. Introduction

2 The UK Government plans to reach net-zero greenhouse gas (GHG) emissions by 2050 under the Paris  
 3 Agreement (HM Government, 2019). To eliminate carbon emissions, the energy mix is moving towards  
 4 electrification, with the increased electricity supply generated from renewable technologies providing  
 5 low-carbon, sustainable energy (National Grid, 2019). Not only is offshore wind one of the fastest  
 6 growing renewable energy technologies, but the UK has the largest installed capacity, which stood at  
 7 7,905 MW in 2018 (The Crown Estate, 2019). To encourage electricity generation from renewable  
 8 sources, the UK government introduced Renewable Obligations (RO) (BEIS, 2012) and later  
 9 established the Contracts for Difference (CfD) scheme which financially supported the rapid  
 10 development of offshore wind farms (OWFs) (BEIS, 2015a). CfDs incentivise the development of  
 11 OWFs by guaranteeing a (typically subsidised) stable sale price for renewable energy electricity  
 12 generation amidst volatile wholesale electricity prices (BEIS, 2018). With the support from CfDs, the  
 13 capacity of OWFs has increased by over 400% while costs have fallen by more than 60% after three  
 14 auction rounds (AR). As shown in Table 1, the successful OWF projects won support in the most recent  
 15 AR3 at a strike price of around £41/MWh. This is lower than the wholesale electricity price and thus  
 16 would count as subsidy-free renewables. This record-low price is likely to encourage further official  
 17 support and faster development of OWFs. Already the UK Government has signed an offshore sector  
 18 deal under which OWF capacity is expected to increase to 30 GW by 2030 (HM Government, 2019).

CfD Allocation round (AR)	Year	Total UK capacity (MW)	Scotland capacity (MW)	Average strike price (per MWh in 2012 prices)	Average wholesale electricity price in 2012 (per MWh)
AR1	2014	1162	448	£117	
AR2	2017	3196	950	£64	£48.2
AR3	2019	5466	466	£41	

19 **Table 1** Three Rounds of Contracts for Difference Allocation of Offshore Wind Energy in UK

20 (Source: BEIS, 2019, 2017, 2015b; Ofgem, 2019.)

1 However, the rapid development of OWFs raises concerns over possible tensions between OWFs and  
2 the fisheries sector, with a potentially reduced seafood supply from the marine environment. Such  
3 conflicts, and associated trade-offs, are appropriately framed in the context of the Food-Energy-Water  
4 (FEW) nexus, which is an integrated approach capturing interconnections, dependencies and linkages  
5 among energy, food and water resources within the environmental, economic and societal scales (FAO,  
6 2014; Hoff, 2011; Salmoral and Yan, 2018). When considering the OWFs and seafood sectors,  
7 however, the interaction is restricted to energy-food, since no fresh water is involved. As the marine  
8 environment is increasingly vulnerable to economic, social and environmental shifts (Austen et al.,  
9 2018), the energy-food nexus between OWFs and seafood production is increasingly becoming the  
10 subject of research.

11 There are indirect macroeconomic linkages between OWFs and seafood production from the energy-  
12 food nexus perspective. On the production side, expanding OWFs could shift resources away from the  
13 seafood sectors, for example through fishermen adapting their skills to meet employment in the OWFs  
14 sector rather than in fishing. This could indirectly affect food supply through increasing the cost of  
15 production, thereby also impacting on household seafood affordability. On the consumption side, both  
16 energy and food are essential commodities in household budgets; energy makes up 8.1% of all UK  
17 household spending with electricity representing half of the household energy budget (Advani et al.,  
18 2013). Food consumed at home comprises 18.3% of budgets, with fish accounting for 5% of total food  
19 spending (ONS, 2019). Through the consumption linkage, potential changes in the price of electricity  
20 generated by OWFs will affect the purchasing power for food. In particular, reducing the cost of OWFs  
21 may have important effects on household electricity consumption and particularly on fuel poverty in  
22 lower-income households.

23 Fishing activities can also be directly affected by OWFs because fishermen are either forbidden to  
24 operate within the OWFs or are reluctant to fish within these areas due to concerns about navigational  
25 safety and inadequate space between turbines for the safe deployment of their gear (Alexander et al.,  
26 2013; Mackinson et al., 2006). Fishermen might switch their fishing grounds away from OWF  
27 development areas, resulting in them fishing in unfamiliar areas. This is likely to lead to lower catches,

1 catches of alternative species with different price profiles or higher increased operating costs for fishing  
2 vessels (Alexander et al., 2013; Gray et al., 2016; Hooper et al., 2015; Mackinson et al., 2006). Conflicts  
3 such as these would result in lower fishing productivity and thus reduced market availability of fish,  
4 which would further impact the overall economy through the macroeconomic linkages. However, whilst  
5 a number of studies have taken the nexus approach between offshore wind energy and seafood from  
6 environmental (e.g. Bailey et al., 2014; Bergström et al., 2014; Hooper et al., 2017) or societal  
7 perspectives (e.g. Hattam et al., 2017; Papathanasopoulou et al., 2015), very little quantitative research  
8 has been undertaken on potential macroeconomic interactions. Therefore we lack a holistic economic  
9 analysis of conflicts and trade-offs between OWFs and seafood sectors, and an evaluation of the  
10 distributional effects across different socioeconomic groups.

11 A Computable General Equilibrium (CGE) model is a comprehensive macroeconomic assessment tool  
12 consisting of a mathematical representation of a market economy based on theoretical general  
13 equilibrium principles. Such models are often used to quantifying the economy-wide impacts of  
14 renewable energy development, including aggregate macro-economic impacts (e.g., Boeters and  
15 Koornneef, 2011; Böhringer and Löschel, 2006) and overall welfare changes (e.g., Böhringer et al.,  
16 2013). Furthermore, a CGE model is suitable for nexus analysis since it can evaluate impacts that  
17 operate through the price mechanism, revealing the interlinkages between economic agents relevant for  
18 nexus elements (Kretschmer and Peterson, 2010). In other words, the CGE model allows assessment  
19 not only of sectoral impacts on nexus elements induced by changes in one nexus element through the  
20 interconnections in the model but also the overall impacts on the economy as a whole. Reviews of CGE  
21 models used to assess the nexus approach are given in Dai et al. (2018), Endo et al. (2020), McCarl et  
22 al. (2017) and Zhang et al. (2018). Specific work focussing on the energy-food nexus regarding biofuels  
23 and agriculture include Arndt et al. (2012), Nkolo et al. (2018), Ringler et al. (2016), Timilsina et al.,  
24 2012, 2011). A CGE model is therefore a suitable tool to quantify the nexus linkage associated with  
25 expansion OWFs and seafood through the production and consumption processes as those identified  
26 above.

1 However, the existing literature focuses only on single components of, rather than the interconnections  
2 between, nexus elements. The CGE model has been applied to assess the wider macroeconomic impacts  
3 of marine renewables (e.g. Allan et al., 2014; Cohen and Caron, 2018; Dalton et al., 2016; Graziano et  
4 al., 2017; Lecca et al., 2017), but no particular attention has been paid to sectoral impacts on seafood  
5 productions. Meanwhile, the CGE model has also been applied to analyse the impacts of regional fishery  
6 policies on seafood production (e.g. Finnoff and Tschirhart, 2008; Floros and Failler, 2004; Pan et al.,  
7 2007; Seung and Waters, 2010) and distribution effects across households (e.g. Hoagland et al., 2015;  
8 Jin et al., 2012). No CGE model has so far been applied in an energy-food nexus framework to evaluate  
9 the impacts of an exogenous shock on both OWF and seafood sectors and the distributional effects on  
10 household expenditures.

11 To fill this gap, we develop a CGE model to comprehensively assess the economic impacts of the  
12 development of OWFs and the interactions with the seafood productions through the incorporation of  
13 macroeconomic linkages from the energy-food nexus perspective. Specifically, this analysis focuses on  
14 how the expansion of OWFs would change seafood and electricity availability and affordability, and  
15 therefore consequently have distributional effects across household groups, using Scotland as the case  
16 study area.

## 17 **2. Method**

### 18 **2.1 Study Area**

19 The marine environment plays an important social and economic role in Scotland. Scotland's offshore  
20 waters are approximately six times the area of its landmass and provide productive and diverse resources  
21 (Scottish Government, 2015). Globally, fish accounts for 17% of animal protein and the demand for  
22 fish is increasing at 2.9% per annum (FAO, 2018). Scotland provides various kinds of seafood from  
23 both sea fishing and aquaculture, and these also act as key inputs to the fish processing sector. In 2017,  
24 almost two thirds of total UK fish landings came from Scotland with vessels based in Scotland landing  
25 453 thousand tonnes of sea fish and shellfish with a value of £316 million gross value added (GVA)  
26 (MMO, 2018; Scottish Government, 2018a). Meanwhile, aquaculture production is growing to meet  
27 the increasing demand for seafood, which generated £436 million GVA in 2017 (Scottish Government,

1 2018a). The increasing fishing and aquaculture production result in fish processing also being an  
2 important seafood sector, contributing £392 million GVA to Scottish economy in 2017 (Scottish  
3 Government, 2018a). Seafood production is culturally and politically important in Scotland and is  
4 expected to remain commercially significant with the constantly increasing domestic and export  
5 demand for seafood (Scottish Government, 2015).

6 Scotland has abundant offshore wind resources and therefore offers huge potential for offshore wind  
7 energy (Scottish Government, 2018b). With access to such a resource, the Scottish Government has set  
8 an ambitious target to generate 100% of Scotland's electricity using renewable technologies, including  
9 offshore wind, by 2020 (Scottish Government, 2018b). In 2018, Scotland had reached 55% of electricity  
10 generated from renewable sources with 217 MW of operational offshore wind and had approval granted  
11 for a further 4.2 GW (Scottish Government, 2018b).

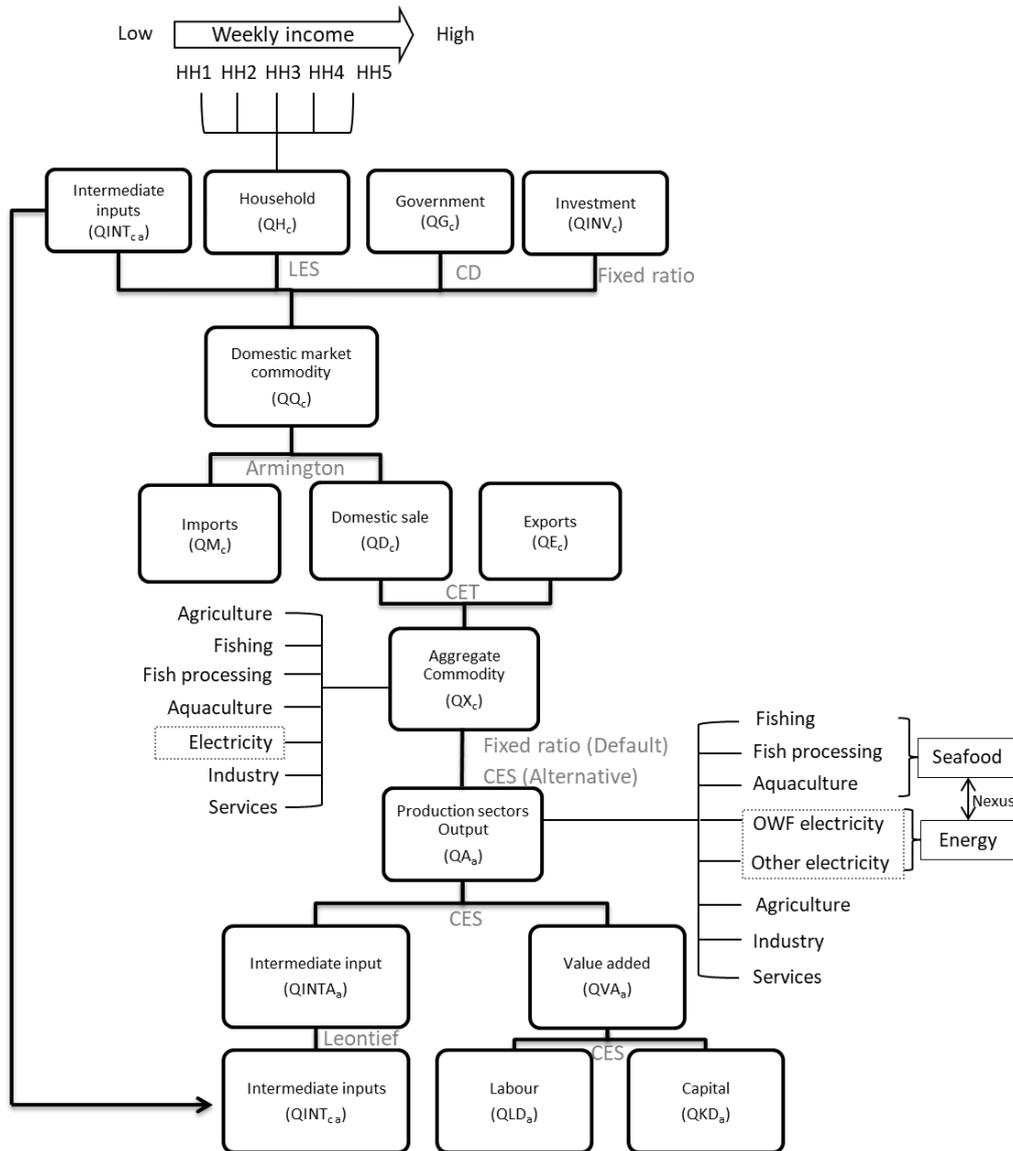
## 12 **2.2 CGE Model Data and Structure**

13 A CGE model is a suitable tool for nexus analysis as it tracks the availability of nexus elements through  
14 the allocation of factors of production and changes in production outputs. It can also evaluate the  
15 affordability of nexus commodities by measuring the changes in prices and thus impact on household  
16 consumption behaviour and welfare distribution.

17 The CGE model used in this study is the Scottish Economy Marine Model (SEMM) and is based on the  
18 International Food Policy Research Institute (IFPRI) Standard CGE model framework (Löfgren et al.,  
19 2002). This has been modified in two major ways. First we incorporate both OWFs and seafood  
20 production as independent sectors within the model economy. Second, households have been explicitly  
21 disaggregated into five income groups to allow the assessment of distributional effects. Figure 1 shows  
22 the model structure and contains information on all key assumptions made for each economic agent.

23 The model is a single-country static CGE model for Scotland and is solved using the General Algebraic  
24 Modelling System (GAMS). Model calibration is based on the latest Social Accounting Matrix (SAM)  
25 for Scotland for 2013 (Katris et al., 2019), which used information from the energy-disaggregated 2010  
26 UK Input-Output table to disaggregate the Scottish electricity sector (Allan et al., 2019) and 2013

1 Scottish IO table to disaggregate the seafood sectors (Scottish Government, 2020). The detailed 8-sector  
 2 SAM is shown as Table A1 in the Appendix A.



3  
 4 **Figure 1** Nested structure of the CGE model

5 In the model, the decisions made by economic agents are the outcome of the optimisation of objectives,  
 6 subject to a number of constraints, within a coherent economy-wide framework. Producers maximise  
 7 their profits subject to technology constraints, where production is represented as a nested structure that  
 8 allows flexibility at different levels. Essentially, the output in each sector is determined by constant  
 9 elasticity of substitution (CES) production functions that permit substitution between inputs based on  
 10 relative price changes. In each sector, the intermediate input is a Leontief composite. This means that  
 11 commodities that make up this composite are combined in fixed proportions.

1 As shown in Figure 1, the model distinguishes eight production sectors resulting in seven commodities,  
2 with three seafood and two electricity production sectors. The seafood sectors are ‘fishing’, ‘fish  
3 processing’ and ‘aquaculture’, whilst for electricity generation ‘OWF electricity’ and ‘other electricity’  
4 are identified separately. The disaggregation of seafood and electricity sectors are further explained in  
5 the Appendix A and the sector decomposition is shown in Table A2. These two electricity sectors are  
6 further combined, with fixed coefficients as the default option, into a single composite electricity  
7 commodity sold in the market. However, as part of the sensitivity analysis, simulations are run in which  
8 the production of the composite electricity commodity is generated via a CES function whose  
9 components are the outputs from the ‘OWF electricity’ and ‘other electricity’ sectors. For all other  
10 commodities, there is a one-to-one association between the production sector and the corresponding  
11 commodity.

12 The SAM is calibrated on 2013 data. At that time Scotland had only 190 MW of installed OWF capacity,  
13 contributing less than 1% of total electricity generation (Scottish Government, 2019). To facilitate  
14 modelling the impact of OWFs, an estimate of the size of this growing sector is required (Phimister and  
15 Roberts, 2017). The sector is expected to make up around 10% of the total UK electricity generation by  
16 2020 (HM Government, 2019).<sup>1</sup> In the initial calibration of the model, we therefore retain the figure for  
17 total electricity generation but adjust the share produced by the OWF sector to 10%. This assumption  
18 provides a useful reference point to identify the present economy-wide impacts of developing OWFs  
19 (Arndt et al., 2012).

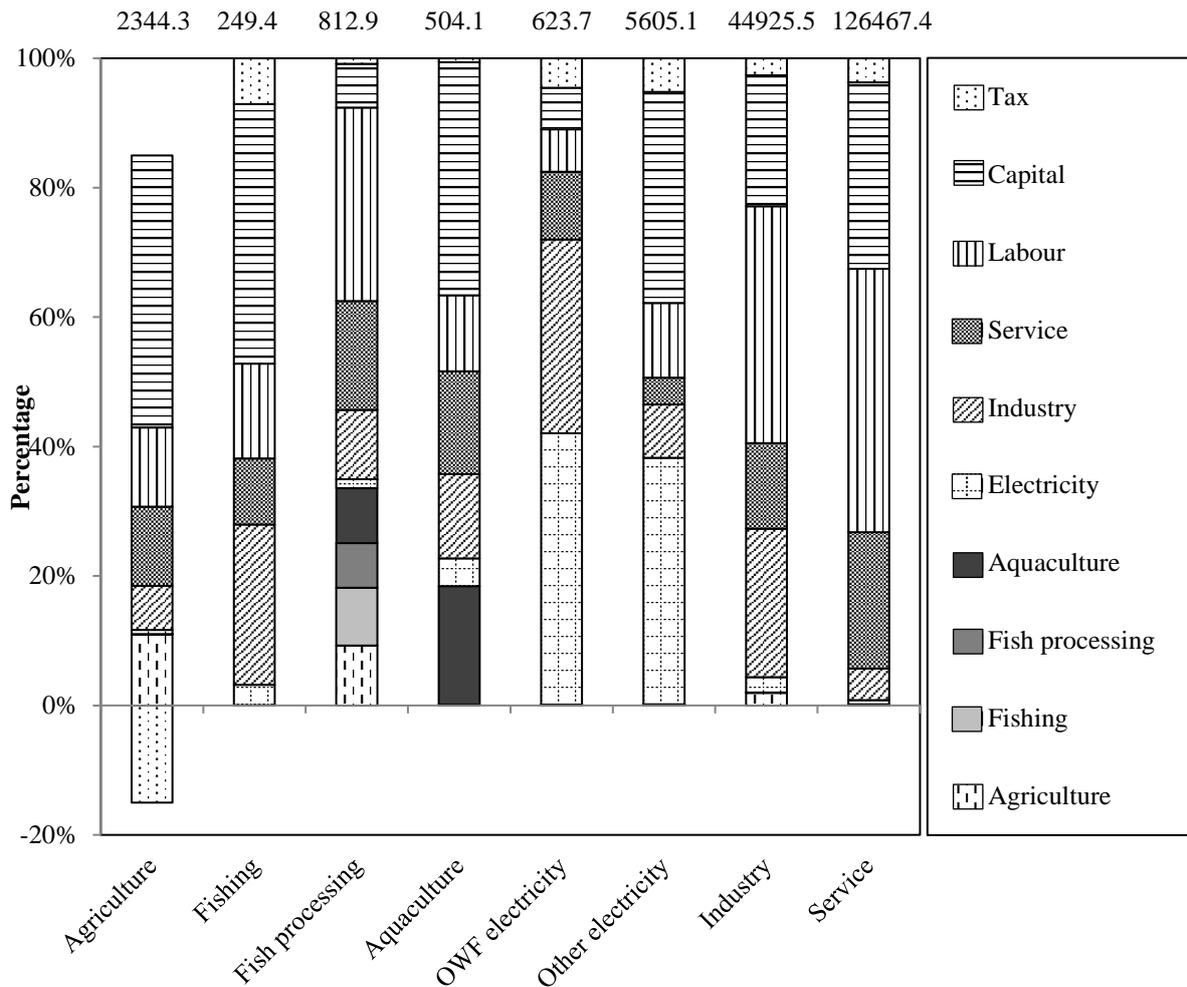
20 The remaining three sectors are agriculture, industry and services. These are highly aggregated but  
21 represent the reactions of the rest of the economy to changes in those production sectors that are of  
22 particular interest, that is the two electricity and three seafood sectors. Aggregation helps to simplify  
23 the model construction but it can lead to bias in the level and distribution of the estimated impacts across  
24 such aggregated sectors (Lenzen, 2011; Miller and Blair, 1985; Su et al., 2010). To test if the  
25 aggregation would lead to significant bias on seafood and electricity sectors, we calculated the Type 1

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<sup>1</sup> OWFs accounted for 8% of the total electricity generation for the UK as a whole in 2018 and almost 7% for Scotland in 2019 (Scottish Government, 2019; The Crown Estate, 2019).

1 multipliers of the 8-sector SAM as an  $8 \times 8$  Leontief inverse matrix. Then we compared the multipliers  
2 for seafood sectors with the fully disaggregated 2013 Scottish IO table and for electricity sectors with  
3 the electricity disaggregated 2010 UK IO table. The results show that there is no significant variation  
4 in seafood and electricity sectors between the aggregated and disaggregated multipliers (Table A3). It  
5 demonstrates that aggregating the rest sectors would not result in huge bias on results of how the impacts  
6 of expanding OWFs distributed among two electricity and three seafood production.

7 The base-year sectoral production input intensities are shown in Figure 2. These reflect the information  
8 given in the 2013 Scottish SAM and describe each sector's production structure. They are important in  
9 determining the way that a sector's competitiveness is affected by variations in input prices, particularly  
10 for capital and labour. Small sectors will tend to have production structures that differ from the average  
11 by a greater extent than do large sectors. This means that their competitiveness will tend to respond  
12 more strongly to the changes in input prices that are generated by exogenous shocks. Like the electricity  
13 sectors, fishing and aquaculture are relatively capital intensive, while fish processing is relatively labour  
14 intensive. Intermediate input demand linkages also create a channel through which a shock in one sector  
15 is transmitted to other sectors. Among the three seafood sectors, fishing and aquaculture are important  
16 intermediate inputs for the fish processing sector while aquaculture needs relatively more electricity as  
17 a production input. Both electricity sectors require a large amount of electricity as an intermediate input.



1  
2 **Figure 2** Production input intensity of production activity sectors with total output above (in £million).  
3 (Data source: Allan et al., 2019; Katris et al., 2019)

4 As this is an open economy model, substitution possibilities are allowed between production for  
5 domestic and non-domestic markets. The model employs the small-country assumption that the country  
6 is a price-taker in the single external market, which comprises both the rest of the UK and the rest of  
7 the world. Export decisions are modelled based on the assumption that producers maximise profit given  
8 domestic and export prices. This occurs under the assumption of imperfect transformation between  
9 domestic sales and exports, which is represented by a constant elasticity of transformation (CET)  
10 function. Furthermore, commodities in the domestic market are supplied by a combination of domestic  
11 production and imports, where imports are determined by the Armington assumption which allows

1 imperfect competition. All the production elasticities are listed in the Appendix A Table A4 and  
2 consumption elasticities can be found in Table A5.

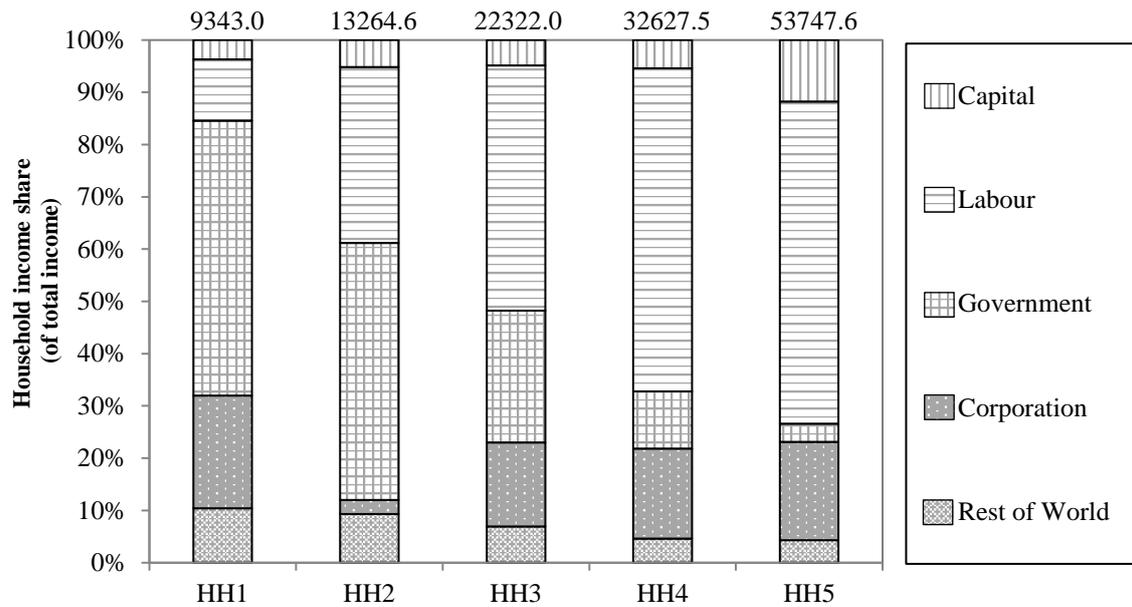
3 The model distinguishes household income quintiles, with weekly income increasing from HH1 to  
4 HH5. As shown in Figure 3, lower income household groups (HH1 and HH2) receive a greater share  
5 of their income from government transfers, in the form of welfare and state pensions, while household  
6 groups with higher income (HH3, HH4 and HH5) are relatively more dependent on wage and capital  
7 income. Household income from wage and capital rental payments is endogenous and driven by  
8 production activities whereas transfers from government are treated here as constant, indexed to the  
9 consumer price index (CPI).

10 To determine aggregate household expenditure, savings, payments of taxes and transfer payments to  
11 other institutions and the rest of the world are subtracted from household income. The commodity  
12 composition of household consumption is determined using a linear expenditure system (LES), which  
13 distinguishes commodities as necessary and luxury goods. Food (i.e. agriculture, fishing, fish  
14 processing) and energy (i.e. electricity) are typically considered as necessary goods which have low  
15 income elasticity. Industry, services and aquaculture are treated as luxury goods for lower income  
16 households but as necessities for higher income households.<sup>2</sup>

17 Government revenues consist of all taxes and transfer payments from other institutions and the rest of  
18 world. Total government expenditures comprise consumption on commodities determined by a Cobb-  
19 Douglas utility function, transfers to other institutions (e.g. social welfare to households), and savings.  
20 All household, government and foreign savings are summed and equal total investment to form the  
21 equilibrium condition. Welfare is measured using the Hicksian equivalent variation (EV) method. This  
22 measures the income needed to make households as well off in the new equilibrium evaluated at  
23 benchmark prices.

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<sup>2</sup> Aquaculture is considered as a luxury good because aquaculture fish is more expensive than capture fish (OECD, 2018).



1  
2 **Figure 3** The share of different income sources for household quintiles with income increasing from  
3 HH1 to HH5 with mean annual income shown at the top of each column (in £million). (Data source:  
4 Katris et al., 2019)

5 Simulation results are sensitive to the model closure rules. For the present model, these are shown in  
6 Table 2. They were chosen to reflect the relative size and openness of the Scottish economy. The fixed  
7 supplies of capital and labour are assumed to be fully employed, with factors mobile between sectors  
8 and equilibrium achieved through economy-wide flexible wages and capital rentals. Finally, the gross  
9 domestic product (GDP) deflator is chosen as the model's numeraire so that price changes in simulation  
10 results are reported relative to this numeraire.

Model closure	Assumption	Justification
Government	Fixed tax rate	To focus on impacts on households, government is simplified.
Current account	Fixed foreign savings	To avoid the misleading welfare effects that appears when foreign savings change.
Saving-investment	Fixed investment	Flexible household saving rate. Correspondence with fixed capital supply.
Factor market	Fixed factor supply	Factors have enough time to adjust to be fully mobile between activities.

1 **Table 2** Summary of model closure assumptions (Source: Löfgren et al., 2002)

2 It is important to note that SEMM is a simulation, not a forecasting, model. Its stripped down character,  
3 and in particular its static nature and fixed aggregate factor supplies, are designed to focus on the key  
4 aspects of the nexus interactions that are our concerns. These are the impacts on the distribution of  
5 resources across sectors and incomes across households.

### 6 **2.3 Scenario Simulations**

7 The nexus implications of the expansion of OWFs are explored through a set of scenarios. In Scenarios  
8 1 and 2 the exogenous shock generates an expansion in the OWF sector but in both simulations this has  
9 no direct effect on the efficiency of fishing sector. However, the model captures the economy-wide  
10 competition for capital and labour and the demand interactions implicit in each sector's supply chain  
11 through the identification of macroeconomic linkages. Scenario 3 takes as the exogenous shock a direct  
12 reduction in the efficiency of the fishing sector. This is assumed to be due to the interference of OWFs  
13 with fishing activities acting as a direct impact of the expansion of OWFs. Table 3 summarizes the three  
14 scenarios considered in this study.

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

1 **Table 3** Simulated OWFs production scenarios for Scotland in the CGE model (Source: BEIS, 2019,  
2 2017, 2015b; Scottish Government, 2018c)

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

13 In Scenario 2, the increased price competitiveness takes the form of a 15% improvement in OWF  
14 efficiency. This reflects the situation in the third round, AR3, of the auction of CfDs where the record-  
15 low average strike price of £41/MWh compared to the average wholesale electricity price of  
16 £48.2/MWh. Scenario 2 therefore shows the impact of an expansion in electricity generation powered  
17 by increasingly efficient renewables and reflects a more optimistic vision for moving towards zero  
18 carbon.

19 The initial share of OWFs in the electricity generation is 10% and the default setting for the model  
20 assumes a fixed ratio between OWFs and other electricity in the domestic production of electricity to  
21 ensure the competitiveness of higher production cost OWFs, as required by government's renewable

1 target. An alternative CES function is available for combining the OWF and other electricity sectors.  
2 With the CES function and an increase in OWF price competitiveness, expanding OWF production will  
3 not only increase the output of electricity as a whole, but also the share in electricity from OWFs. In  
4 this case, the elasticity between OWF and other electricity represents the sensitivity of the trade-off that  
5 the national grid is prepared to make across different generation types. For that reason we test how  
6 sensitive the results in Scenario 1 and 2 are to variation in this elasticity value.

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

### 12 **3. Results**

#### 13 **3.1 Sectoral impacts on production activities and commodity sales**

14 In Table 4 we report the percentage changes in the level and price of the eight sectoral production  
15 outputs (QA, PA) and the level and price of the seven domestic market commodities (QQ, PQ) for all  
16 three scenarios. Results for other important variables (i.e., value-added, QVA; intermediate input used,  
17 QINTA; imports, QM; exports, QE; and their prices) are shown as percentage changes in the Appendix  
18 B (TablesB1, and B2).

19 First, note that in each simulation reported in Table 4, the proportionate changes in the domestic output  
20 for ‘OWF electricity’ and ‘other electricity’ sectors are exactly the same. This is because, as discussed  
21 in Section 2.2, the two electricity sectors are assumed to have a fixed share in the electricity generation  
22 mix. Although the percentage increases in the domestic OWF electricity outputs are similar in both  
23 Scenario 1 (+5.34%) and Scenario 2 (+5.81%), the output price changes are quite different (-5.16% and  
24 -13.83% respectively). In Scenario 1 the positive impact of the subsidy outweighs the negative impact  
25 from the higher cost of OWFs in Scenario 1, so the reduction in output price is much less than in  
26 Scenario 2.

1 However, the increase in electricity commodity sales is greater in Scenario 1. The explanation reflects  
2 the relatively large amount of electricity that is used in the production of electricity. In Scenario 1, OWF  
3 production is expanding together with a reduction in the efficiency with which it is produced: this  
4 implies that the electricity input per unit of output of OWF increases. However, in Scenario 2 the input  
5 of electricity per unit of OWF falls. This difference in the demand for electricity as an intermediate  
6 input accounts for the counterintuitive electricity sales results.

7 Where electricity production expands, other elements of the economy, apart from the industry sector,  
8 are typically negatively impacted. The expansion of OWFs requires the net transfer of labour and capital  
9 from other sectors. This includes the seafood sectors. As argued earlier, being smaller sectors they are  
10 likely to have more idiosyncratic cost structures. This implies that these sectors are more likely to  
11 deviate from the average reaction to exogenous shocks and are more sensitive to movements in the  
12 prices of production inputs. Among three seafood sectors, the fishing and aquaculture sectors are most  
13 strongly affected. This is primarily because - similarly to the electricity sectors - they are relatively  
14 capital-intensive, as shown in Figure 2. The fish processing sector suffers some knock-on effects from  
15 reductions in the capture and aquaculture fish supplies. The sales of seafood tend to change less than  
16 their outputs because more expensive seafood results in reduced demand, both in domestic and export  
17 markets. Also as a result of inter-sectoral movement in capital and labour, production in aggregated  
18 agriculture and services sectors falls, whilst the output of the industry sector increases slightly, being  
19 an important input for electricity production. The sectoral domestic production directly impacts the  
20 corresponding commodity sales and prices.

21 In Scenario 3, the reduced productivity in the fishing sector has negative impacts, particularly on the  
22 seafood sectors. The output of the fishing sector falls by over 13% with a 0.58% increase in price.  
23 Outputs in fish processing, aquaculture and agriculture also decrease due to a reduction in fish to be  
24 used as a production input. The non-food sectors experience minor output increases, benefited from  
25 labour and capital released from the small seafood sectors. The decline in domestic production of  
26 seafood also negatively impacts seafood export and seafood demand so that the import and commodity  
27 sales both decrease.

Variable	Scenario 1	Scenario 2	Scenario 3
<b>Domestic production activities (Supply)</b>			
<i>Production sector Output (QA)</i>			
Agriculture	-0.36	-0.71	-0.02
Fishing	-2.75	-3.36	-13.49
Fish processing	-1.41	-1.86	-4.24
Aquaculture	-5.49	-5.11	-1.49
Other electricity	5.34	5.81	0.06
OWF electricity	5.34	5.81	0.06
Industry	0.33	-0.11	0.07
Services	-0.25	-0.06	0.02
<i>Price of Domestic Output (PA)</i>			
Agriculture	0.12	0.15	-0.02
Fishing	0.07	0.05	0.58
Fish processing	0.03	0.03	0.17
Aquaculture	0.11	0.07	-0.03
Other electricity	-0.22	-0.75	-0.02
OWF electricity	-5.16	-13.83	-0.01
Industry	-0.01	-0.01	0.00
Services	0.02	0.05	0.00
<b>Domestic sale commodities (Demand)</b>			
<i>Domestic market commodity sales (QQ)</i>			
Agriculture	0.02	-0.16	-0.11
Fishing	-1.31	-1.68	-3.87
Fish processing	-0.35	-0.24	-0.63
Aquaculture	-3.35	-3.23	-2.33
Electricity	3.98	1.83	0.01
Industry	0.33	0.01	-0.01
Service	-0.21	0.05	0.00
<i>Price of domestic market commodity (PQ)</i>			
Agriculture	0.12	0.15	-0.01
Fishing	0.22	0.24	1.67
Fish processing	0.08	0.10	0.32
Aquaculture	0.30	0.24	-0.11
Electricity	-0.72	-2.10	-0.01
Industry	-0.01	-0.01	-0.01
Service	0.03	0.06	0.00

1 **Table 4** Percentage changes (%) in production activity and commodity sales for different sectors

## 2 **3.2 Changes in household income and welfare distribution**

3 Table 5 shows the differences in the distributional impacts across household groups. In all scenarios the  
4 impact on incomes is small across all households. In Scenarios 1 and 2, as OWFs expand, other sectors

1 are forced to release both capital and labour. Because the electricity sectors are relatively capital  
 2 intensive, the economy-wide capital rental rate rises and the wage falls. Household incomes depend  
 3 more heavily on wage payments so all households show slightly reduced incomes. The increasingly  
 4 inefficient OWFs expansion, as outlined in Scenario 1, results in slightly larger negative changes in  
 5 household incomes. Moreover, the incomes of lower-income households vary less than those of higher-  
 6 income households, whose incomes rely more heavily on wages and capital rental (Figure 3). The  
 7 change is similar in Scenario 3 but the variations in wage and capital rentals are so small that there are  
 8 only minor impacts on household incomes.

9 The household welfare is valued by EV in income. This shows that under Scenario 1 welfare falls for  
 10 all household quintiles with no consistent trend over household income. In Scenario 2 all households  
 11 experience a welfare improvement with lower income households consistently benefitting the most.  
 12 Decreased fishing productivity in Scenario 3 again has only slight impacts on households, as fishing is  
 13 a small sector in the economy.

Variable	Scenario 1	Scenario 2	Scenario 3
<i>Household income</i>			
Labour wage	-0.13	-0.11	0.02
Capital rent	0.26	0.32	-0.03
HH1	-0.01	0.00	0.00
HH2	-0.03	-0.02	0.01
HH3	-0.05	-0.04	0.01
HH4	-0.07	-0.05	0.01
HH5	-0.05	-0.03	0.01
<i>Household welfare (equivalent variation in household income)</i>			
HH1	-0.20	0.16	0.00
HH2	-0.20	0.12	0.00
HH3	-0.21	0.10	0.00
HH4	-0.21	0.07	0.00
HH5	-0.17	0.07	0.00

14 **Table 5** Percentage change (%) in household income, commodity consumption and welfare

### 15 **3.3 Macroeconomic impacts**

16 The macroeconomic results show that the expansion in OWF output accompanied by a reduction in  
 17 OWF efficiency, as in Scenario 1, has an overall negative impact on GDP (-0.21%). In contrast, the

1 increased efficiency of electricity from OWFs in Scenario 2 produces a small increase in GDP of 0.08%.

2 In Scenario 3, decreasing productivity in the fishing sector has a negligible impact on the economy at a

3 macro scale.

4 For all three simulations, the proportionate changes in real absorption are reported in the second row of

5 Table 6. Real absorption is defined as the sum of private consumption, government spending (results

6 shown in Appendix B Table B3) and gross investment (assumed to be fixed in the model). GDP equals

7 real absorption plus the trade balance (total exports – total imports). The proportionate change in GDP

8 is the weighted sum of the proportionate changes in real absorption and the trade balance. In first two

9 scenarios, the proportionate change in the real absorption dominates in determining the change in GDP.

10 In Scenario 1, the proportionate change in GDP is heavily influenced by the negative change in real

11 absorption arising from decreased household consumption. In contrast, in Scenario 2 GDP increases as

12 cheaper electricity causes the real absorption to increase significantly to cover the trade deficit. There

13 is no significant change in Scenario 3. The total exports decrease slightly reflecting the falling domestic

14 production of seafood whereas the total imports also fall slightly due to decreasing demand. The decline

15 in total exports and total imports balance the trade deficit, together with no significant change in real

16 absorption, resulting in no change in GDP.

Variable	Scenario 1	Scenario 2	Scenario 3
Gross domestic product (GDP)	-0.21	0.08	0.00
Real absorption	-0.25	0.10	-0.01
Total exports	0.10	0.03	-0.04
Total imports	0.15	0.05	-0.05

17 **Table 6** Percentage changes (%) in macroeconomic variables in different scenarios simulated

18 **4. Discussion**

19 **4.1 Model results: implications for energy security and the macro-economy**

20 Concerns over electricity price volatility have previously been raised in part because of fear that

21 renewable technology policies aimed at reducing carbon emissions might result in fuel poverty, given

22 that electricity is a necessity to all households (Advani et al., 2013; Teller-Elsberg et al., 2016). The

1 results from Scenario 1 show that increasingly inefficient OWF production can be stimulated by a CfD  
2 scheme that incorporates subsidised price reductions. However, the energy security to households is not  
3 increased because energy affordability falls as a result of lower incomes. The increased electricity  
4 production in this case mainly goes to government consumption (Table B3) and exports (Table B2).  
5 Only when the reduced price of OWF output is driven by increased efficiency, as in Scenario 2, do  
6 households experience increased energy affordability and a corresponding rise in household  
7 consumption. Based on differential patterns of consumption, electricity price changes have differential  
8 impacts on the welfare of different household groups. An analysis of household energy use in the UK  
9 revealed that energy makes up 16% of lower-income household spending but for just 3% of higher-  
10 income household spending (Advani et al., 2013). Variation in the electricity price therefore makes the  
11 welfare of the lowest income group (HH1) the most sensitive to the modelled energy shocks discussed  
12 in this paper. The record-low price of OWFs (simulated in Scenario 2) in AR3 implies significant  
13 reduction in fuel poverty through much cheaper electricity. This especially helps lower-income  
14 households as against the varying electricity prices driven by fossil fuel price volatility (Fuss and  
15 Szolgayová, 2010).

16 It is often argued that growth in renewable energy generation brings economic benefits through  
17 increased investment and employment (Phimister and Roberts, 2017). However the model results for  
18 Scenario 1 demonstrate that although the subsidy under the CfD scheme stimulates the development of  
19 OWFs when the cost is higher than generation using fossil fuels, it has a negative impact on GDP. These  
20 results suggest that the development of OWFs would only have conventional economic benefits when  
21 the cost is brought down so that production becomes subsidy-free, as in Scenario 2.<sup>3</sup> Furthermore, the  
22 macroeconomic benefits are highly related to the local supply chain; higher local content could generate  
23 greater GDP growth (Graziano et al., 2017) and employment (Gilmartin and Allan, 2015). Based on  
24 Scenario 1 results, the current local content for OWF supply chain is not enough to bring economic  
25 benefits though output in the industry sector has increased in response to higher demand from the

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<sup>3</sup> It is important to note that the conventional GDP calculation does not take into account any environmental improvements that would accompany Scenarios 1 and 2.

1 expansion in OWFs. In addition, the SEMM has a highly aggregated industry sector. As indicated by  
2 the multiplier (Table A3), the aggregated multiplier would misrepresent industries in its subcategory,  
3 which would lead to underestimate the impacts from local supply chain. With subsidy-free production  
4 and the anticipated increase in local supply content, the enhanced economic benefit is likely to further  
5 encourage the development of OWFs, in accordance with the net-zero emission target of the Scottish  
6 Governments.

#### 7 **4.2 Model results: implications for food security**

8 Optimism over subsidy-free OWFs is countered by uncertainty over possible trade-offs between OWFs  
9 and seafood production, and further detrimental effects that changing seafood supplies may have on  
10 food security. Expanding production of OWFs under both the higher and lower cost cases (Scenarios 1  
11 and 2 respectively) is expected to have negative impacts on seafood production because production  
12 factors (labour and capital) are bid away by expanding OWFs. The major direct and negative impact on  
13 seafood production is through the displacement of fishing effort caused by OWFs and this is the focus  
14 of Scenario 3. Such a reduction in fishing productivity and the accompanying decreases in production  
15 in seafood sectors would normally be ignored in a macroeconomic analysis of OWFs. Our results show  
16 that the negative impacts of a fall in fishing productivity are significant for the fishing sector, but would  
17 be largely confined to the three seafood sectors. Declining fish supplies from the fishing sector further  
18 negatively impacts the fish processing and aquaculture sectors through the macroeconomic linkages  
19 because fish is clearly an important intermediate input. Similar concerns have also been observed for  
20 the agriculture and biofuel nexus where biofuel production raises agricultural prices through  
21 competition for limited resources such as land, with a corresponding impact on price of processed food  
22 (Ringler et al., 2016).

23 Furthermore, the competitiveness of seafood commodities in foreign market would fall. In Scotland,  
24 the seafood production (mainly fishing and aquaculture) is export oriented, which makes the demand  
25 for seafood commodities sensitive to foreign price changes (Graziano et al., 2018). Our results show  
26 falling seafood exports in both Scenario 1 and 2 as response to fall in foreign price (Table B2). Reduced  
27 export demand also makes the domestic seafood productions decrease.

1 The model results show minor effects on food security in terms of household affordability. Unlike  
2 electricity, which is a necessary good for households, seafood commodities are substitutable by other  
3 food sources so that the small increase in seafood prices in the model has a negligible impact on  
4 households. However, the model identifies the macroeconomic linkages whereby the lower supply of  
5 seafood leads to higher seafood prices through the price mechanism and eventually reduces household  
6 affordability. Therefore if, as expected, the scale of the OWF sector increases, the impacts would  
7 become significant through macroeconomic linkages, with the reduction in the supply and affordability  
8 of seafood resulting in lower food security (e.g. Pelletier et al., 2014; Smith et al., 2010). In these  
9 contexts, seafood security is potentially strongly related to further development of OWFs. Therefore,  
10 these impacts on the seafood sector should be carefully considered under the nexus framework when  
11 assessing further development of OWFs in response to net-zero policy targets.

### 12 **4.3 Sensitivity analysis**

13 The sensitivity analysis maps the reaction of sectoral output values to variations in the elasticity of  
14 substitution ( $\sigma_a^{el}$ ) between the two electricity production sectors in the generation of the composite  
15 electricity commodity. This elasticity reflects the degree to which a low-carbon offshore wind  
16 generation technology is substitutable for other electricity generation, which relates to the evolution of  
17 technical change between OWFs and fossil fuels (Acemoglu et al., 2012). At present OWFs are  
18 imperfect substitutes for non-intermittent fossil fuels as an intermittency energy source due to limited  
19 technology of storability and transmission to the national grid (Madrigril and Stoft, 2012; Timilsina et  
20 al., 2012) .

21 Increasing the substitution elasticity where the price of OWF output is falling has two effects. First, it  
22 increases the output of the OWF sector, as OWF electricity is substituted for other electricity output.  
23 Second, the impacts of OWFs on the electricity commodity price will increase as the importance of the  
24 OWF sector in the electricity commodity composite rises. The absolute size of the negative impacts on  
25 seafood sectors would also be reduced in line with the falling price of electricity. To test this, the  
26 elasticity ( $\sigma_a^{el}$ ) is increased under Scenarios 1 and 2. Results for the default fixed share ( $\sigma_a^{el} = 0$ ) are  
27 compared to those where there is some flexibility, with the two sectors as complements ( $\sigma_a^{el} = 0.5$ )

1 and weak substitutes ( $\sigma_a^{el} = 1.5$ ). The simulations are also instructive in that they identify the ease with  
 2 which the share of OWFs in total electricity generation could be increased. These results are shown in  
 3 Table 7.

4 As the elasticity of substitution between electricity sectors increases, the changes in output of the OWF  
 5 sector becomes more significant and the impact on the other electricity sector is reduced, reflecting the  
 6 reduction in the price of OWF production as against the other electricity sector. This is particularly the  
 7 case for Scenario 2 where allowing substitution between two sectors increases the share of OWF in total  
 8 electricity generation to 12% as it becomes a more price competitive energy source.

9 Raising the elasticity limits the proportionate reduction in the output of the fishing and fish processing  
 10 sectors, but the change is relatively small. For aquaculture the same pattern emerges but the effect of  
 11 varying the elasticity is greater. This is especially the case in Scenario 2, where the sector contracts by  
 12 5.11% with the default value but slightly increases by 0.85% when the two electricity generating sectors  
 13 are substitutes. It is expected that being a luxury good, aquaculture is sensitive to price change so that  
 14 aquaculture could benefit from the lower electricity price in Scenario 2.

Production sectors	Default (Fixed coefficients)	Complementary ( $\sigma_a^{el} = 0.5$ )	Substitutable ( $\sigma_a^{el} = 1.5$ )
Scenario 1			
Fishing	-2.75	-2.04	-1.99
Fish processing	-1.41	-1.01	-1.01
Aquaculture	-5.49	-4.02	-3.78
Other electricity	5.34	4.37	4.08
OWF electricity	5.34	7.05	12.31
Share of OWF	10.00	10.24	10.72
Scenario 2			
Fishing	-3.36	-1.18	-0.86
Fish processing	-1.86	-0.63	-0.56
Aquaculture	-5.11	-0.39	0.85
Other electricity	5.81	2.85	1.70
OWF electricity	5.81	10.37	25.66
Share of OWF	10.00	10.67	12.09

1 **Table 7** The sensitivity of selected sectoral outputs to alternative values of the elasticity  $\sigma_a^{el}$  (%  
2 change in sectoral output of seafood production and electricity generation sectors)

### 3 **4.4 Limitations**

4 A CGE modelling framework is a powerful assessment tool for energy-food nexus analysis, but the  
5 present study still suffers from a number of limitations. The simulation results have focused primarily  
6 on the production and consumption interaction between OWFs and seafood from the macroeconomic  
7 perspective. Note that the model identifies only the competition between energy and marine sectors for  
8 economy-wide factors of production, labour and capital. In the approach adopted here we do not specify  
9 any direct systematic link as the result of the competitive use of scarce marine resources, such as the  
10 replacement of fishing grounds with OWF areas (Berkenhagen et al., 2010). Although aquaculture and  
11 fish processing are not directly affected by spatial conflict with OWFs, they would have the knock-on  
12 effects from reduced fish supply and the whole seafood production would be impacted from the nexus  
13 perspective. Furthermore, the model does not take into account that there may be positive impacts of  
14 OWFs on fish stocks with potential benefits to fisheries. These result from the artificial reef effects  
15 and/or the *de facto* fishery exclusion zones created by OWFs (Bergström et al., 2014; Langhamer, 2012;  
16 Westerberg et al., 2013). The assumptions underlying all these features should be addressed in future  
17 iterations of the SEMM model. Future work could focus on improving the model structure to allow  
18 competition and reallocation of marine areas, which could provide a stronger direct link between OWFs  
19 and fishing activities and knock-on effects on seafood production (Qu et al., in preparation). A further  
20 step could be the adoption of an integrated approach combining biological/ecological and CGE models  
21 to take the assessment to the ecosystem level.

## 22 **5. Conclusion and Policy Implication**

### 23 **5.1 Conclusion**

24 With fast development and rapidly falling costs, OWFs are likely to play an important role in increasing  
25 energy security and reaching the net-zero emission target of the UK Government. In particular, the  
26 recently announced record-low strike price of OWFs from AR3 will encourage further deployment of

1 OWFs. However, expanding OWFs may bring conflicts with seafood supply because of indirect impacts  
2 through macroeconomic linkages and direct impacts through displacing fishing effort, which could be  
3 described in the energy-food nexus approach. Therefore, identifying, quantifying and managing the  
4 nexus between offshore wind energy and seafood supply will be of great importance in achieving the  
5 GHG target without jeopardising other economic and social goals.

6 This research fills a gap in existing socioeconomic assessments by principally focusing on the sectoral  
7 impact of the expansion of OWFs on seafood production and on the associated household income,  
8 consumption and welfare effects across different household groups. We develop a CGE model to  
9 compare the macroeconomic impacts of OWF electricity costs that are higher (AR2) or lower (AR3)  
10 than the wholesale electricity price and to assess the direct physical impacts of OWFs on fishing  
11 activities. In particular, this model is designed for applied energy-food nexus analysis in the marine  
12 context with separately-identified OWF and seafood sectors.

13 This analysis suggests that the overall economic impact of OWFs would be negative when the cost of  
14 OWFs is higher than the wholesale electricity price but positive when their cost is lower. From the  
15 energy-food nexus perspective, high-cost OWFs would not enhance energy security. Although the  
16 production of OWFs could be stimulated by the CfD scheme, households would not benefit. Only low-  
17 cost OWFs would benefit energy security and improve welfare by both expanding production and  
18 making electricity cheaper for households. Food security is slightly decreased through the  
19 macroeconomic linkages as an expansion in the output of OWF sector creates negative impacts on  
20 seafood sectors by bidding away the production factors. The direct impacts through displacement of the  
21 fishing effort are confined to the three seafood sectors, with negligible impacts on the rest of the  
22 economy as the affected sectors are small. As for the distributional effects on household groups, lower  
23 income households are sensitive to electricity price changes as electricity is an essential commodity for  
24 households. This suggests that low-cost OWFs would help mitigate fuel poverty, especially for the  
25 lowest-income households.

## 26 **5.2 Policy implications**

1 To meet the ambitious targets for future net-zero emissions, large-scale production of offshore  
2 renewables in Scotland will be expected. The approach taken in this study can easily be adapted to  
3 analyse the impact of other offshore renewable energy sectors including, for example, floating OWFs  
4 and particularly tidal and wave energy as planned in Scotland (Scottish Government, 2015). As these  
5 other offshore renewable energies still operate under high cost, our Scenario 1 results suggest that the  
6 economy would be negatively impacted through increased production of electricity using such  
7 technologies though they are low-carbon intensive. The CfD scheme serves to stimulate the production  
8 of marine renewables so that they contribute towards the decarbonisation of electricity but in a costly  
9 way which reduces households' welfare. Only when the cost has declined to a competitive, subsidy-  
10 free level could the offshore renewables bring positive impacts on the economy and provide cheaper  
11 electricity to benefit households. In particular, given that electricity price plays an important part in  
12 consumer budgets, especially those from lower income households, relevant renewable energy policies  
13 should carefully consider their distributional effects.

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

24 The results from the sensitivity analysis highlight the importance of substitution of OWFs and this also  
25 applies to other offshore renewables. The renewable energy share in overall electricity generation  
26 depends to a degree on the elasticity of substitution between the renewable and conventional electricity  
27 generation. When the renewable energy still has high production cost, a subsidy could help increase its

1 share in total electricity generation but even with high substitution values will only make slow progress.  
2 In comparison, sensitivity analysis results where renewables have low production cost demonstrate that  
3 the greater replacement of other conventional electricity with renewable energy implies a more rapid  
4 move towards low-carbon generation. The strong substitution relationship might become more feasible  
5 as innovation widens the range of technological possibilities, such as improvements in storability  
6 (Acemoglu et al., 2012). If high substitution is achievable, from the macroeconomic perspective,  
7 renewable energy targets to support net-zero goals will become more easily attainable.

8 As long as OWFs are expanding, there will typically be negative impacts on the seafood sectors through  
9 the macroeconomic linkages, mainly driven by the general equilibrium competition for production  
10 factors. Although reductions in seafood production do not have profound effects across the economy as  
11 a whole, these effects may be locally or regionally significant, and fishing activities are still traditionally  
12 and culturally important for Scotland (Scottish Government, 2015). Possible mitigation policies include  
13 compensation for fishing businesses operating near planned OWFs areas or the creation of a common  
14 fund allowing fishermen to diversify (Alexander et al., 2013). The Oil and Gas UK Fishermen's  
15 Compensation Fund, which compensates for damages to fishing gear from oil and gas infrastructures,  
16 could set a precedent for similar funds for OWFs (BEIS, 2018b). Quantifying the negative economic  
17 implications on the fishing sector will help to determine the scale of funding required through such  
18 mitigation schemes.

19 In summary, this CGE model is a useful tool to help improve quantitative understanding of the energy-  
20 food nexus between OWFs and seafood production through the macroeconomic linkages. The results  
21 obtained clearly support the view that it is important to account for the economic linkage of OWFs and  
22 seafood production. It could be a highly useful tool to support policy design to balance conflicting food  
23 security, energy security and net-zero emission goals in the context of the marine environment.

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## 1 **Appendix A** 8-sector SAM in the SEMM

2 The basic 2013 Scottish SAM table is taken from Katris et al. (2019). It records the flows of incomes  
3 and expenditures through the Scottish economy. It is disaggregated to 30 production activities and five  
4 households quintiles based on weekly income. To analysis the nexus linkage between OWFs and  
5 seafood production, three seafood sectors and two electricity sectors have been disaggregated from the  
6 original 30 aggregated sectors. The fishing sector is disaggregated from the original ‘Agriculture,  
7 forestry and fishing’ sector; the fish processing and aquaculture is disaggregated from the ‘Food (and  
8 Tobacco)’ sector; and the OWF electricity sector is disaggregated from the ‘Electricity, transmission  
9 and distribution’ sector. Information on the production technologies of the three seafood sectors comes  
10 from the Scottish input-output (IO) table as these three sectors are already identified as independent  
11 sectors (Scottish Government, 2020). After separating the fishing sector, the rest remains as the  
12 agriculture sector. After disaggregation of the fish processing and aquaculture, the rest ‘Food and  
13 (Tobacco)’ is aggregated into the industry sector. Unlike seafood, the OWF electricity sector is not  
14 specifically recorded in the Scottish IO accounts. As mentioned in Section 2.2 of the text, the SEMM  
15 assumes 10% of electricity generated by OWFs so that the total cost of the OWF electricity sector is  
16 determined. Once the total output of OWFs is determined, the shares of each input across individual  
17 commodities (i.e., intermediate inputs) and value-added (i.e., labour and capital) are multiplied by the  
18 total cost listed in the UK IO table disaggregated by electricity production sectors (Allan et al., 2019).  
19 The remainder in the electricity account consists of the other electricity sector. The rest 27 activities in  
20 the original SAM are aggregated into the industry or service sector.

21 The approach to disaggregate the household final demand on three seafood sectors is based on the  
22 methodology by Emonts-Holley and Ross (2014) and Katris et al. (2017). In general, the share of home  
23 consumption in total consumption of each commodity is estimated based on the household surveys.  
24 There are two available ones, Household Final Consumption Expenditure (HHFCE) matrix (Scottish  
25 Government, 2009) and Living Cost and Food Survey by ONS (ONS, 2014). The previous 2009  
26 Scottish SAM table also provide reliable information on household consumption on three seafood  
27 sectors (Ross and Emonts-Holley, 2016). Using these data, commodity consumption is disaggregated

1 across household groups. The two electricity activities are aggregated into one commodity to be  
2 consumed by household so there is no need to disaggregate electricity consumption.

3 All elasticities assumed in the SEMM are concluded in Table A4 and A5. The source of elasticities is  
4 previous studies and listed in the tables. The priority choice on elasticity is UK-based works (e.g.,  
5 Defra). When the elasticity for UK is not available, the SEMM adopts assumption based on developed  
6 country data (e.g., FAO).

7

**Table A1 Aggregated 8-sector 2013 Social Accounting Matrix for Scotland in SEMM**

	sec_ag	sec_fi	sec_fp	sec_aq	sec_of	sec_el	sec_in	sec_se	com_ag	com_fi	com_fp	com_aq	com_el	com_in	com_se	lab	cap	hh1	hh2	hh3	hh4	hh5	cor	gov	invsav	row	total	
sec_ag									2344.3																		2344.3	
sec_fi										249.4																	249.4	
sec_fp											812.9																812.9	
sec_aq												504.1															504.1	
sec_of													623.7														623.7	
sec_el													5605.1														5605.1	
sec_in														44925.5													44925.5	
sec_se															126467.4												126467.4	
com_ag	368.2	0.0	75.1	0.4	0.8	10.0	880.6	133.9										98.6	138.4	171.8	206.8	270.5		10.8	86.5	969.2	3421.6	
com_fi	0.1	0.0	72.9	0.0	0.0	0.0	1.5	4.1										1.1	1.6	1.9	2.3	3.0		0.2	-7.6	225.3	306.4	
com_fp	1.6	0.0	55.9	0.3	0.0	0.0	25.4	68.7										26.8	38.6	47.7	54.3	75.0		0.0	4.6	743.1	1142.3	
com_aq	0.1	0.0	68.9	92.3	0.0	0.1	1.3	7.5										2.3	3.2	4.0	4.8	6.2		0.3	-6.6	454.5	638.8	
com_el	20.7	7.9	11.5	21.5	261.5	2135.8	1056.0	834.1										262.4	353.3	386.1	367.4	427.0		0.0	63.5	1961.2	8169.9	
com_in	229.4	61.8	87.1	65.7	186.7	460.4	10299.0	6140.9										519.5	748.6	925.6	1053.5	1454.0		547.3	10442.0	27806.3	61027.8	
com_se	409.1	25.5	136.5	80.0	65.4	233.3	5957.5	26682.5										4509.0	6546.7	8682.0	11474.9	16773.9		31106.3	3736.4	34770.1	151189.0	
lab	410.4	36.5	243.3	59.3	40.8	647.4	16435.1	51466.6																			69339.4	
cap	1408.7	100.1	54.8	181.6	40.1	1827.9	9083.7	36404.5																			49101.4	
hh1																1095.4	345.7							2012.3	4915.6		974.0	9343.0
hh2																4459.9	686.3							358.6	6521.8		1238.0	13264.6
hh3																10474.3	1086.7							3579.5	5628.8		1552.7	22322.0
hh4																20170.8	1771.8							5609.0	3560.8		1515.1	32627.5
hh5																33139.0	6306.6							10122.8	1878.8		2300.4	53747.6
cor																		32527.2	104.5	241.6	675.9	1886.2	4879.7	0.0	16742.5		-706.2	56351.4
gov	-504.1	17.6	6.9	3.0	28.3	290.1	1185.5	4724.7										6377.2	958.6	2605.6	4634.0	7772.6	16359.4	5981.2		2407.1	12644.9	65492.6
invsav																			157.8	114.6	562.7	1830.0	5495.8	28688.0	-5420.6		-8400.5	23027.9
row									1077.3	57.0	329.4	134.6	1941.1	16102.3	24721.6			2702.4	2472.4	6230.3	7974.7	8002.9	0.0	0.0	6302.0		78048.3	
total	2344.3	249.4	812.9	504.1	623.7	5605.1	44925.5	126467.4	3421.6	306.4	1142.3	638.8	8169.9	61027.8	151189.0	69339.4	49101.4	9343.0	13264.6	22322.0	32627.5	53747.6	56351.4	65492.6	23027.9	78048.3		

**Table A2** Sector decomposition of SEMM

8-sector SAM in SEMM	sector titles	2013 30-sector SAM table (Katris et al., 2019)	2013 98-sector Scottish IO (Scottish Government, 2020)	2010 26-sector UK IO table (Allan et al., 2019)
1	Agriculture	1		
2	Fishing	1	4	
3	Fish processing	5	10	
4	Aquaculture	5	5	
5	OWF electricity	16	46	S12
6	Other electricity			S10, S11, S13
7	Industry	2 - 15, 17 - 20		
8	Service	21 - 30		

**Table A3** Comparison of Type 1 multiplier from 8-sector SAM in SEEM, 98-sector Scottish IO and 26-sector UK IO

	8×8 Aggregated SAM in SEMM	2013 98-sector Scottish IO (Scottish Government, 2020)	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		

**Table A4** Production function behaviour parameters (based on Allan et al., 2014; Lecca et al., 2014)

Production Sectors	Elasticity of Substitution			
	Elasticity of aggregate input ( $\sigma_a^a$ )	Factor substitution elasticity ( $\sigma_a^{va}$ )	Elasticity of export transformation ( $\sigma_c^t$ )	Armington substitution elasticity ( $\sigma_c^q$ )
Agriculture	0.3	0.3	2	2
Fishing				
Fish processing				
Aquaculture				
Offshore wind electricity				
Other electricity				
Industry				
Service				

**Table A5** 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 (Defra, 2000) 0.27 (Defra, 2000)
Fishing	0.70	0.60	0.50	0.40	0.30	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 (Defra, 2000)
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 ( $\varphi$ )						
Frisch	-7.27	-5.34	-3.07	-1.92	-1.20	Creedy and Dixon (1998) $\log(-\varphi) = a - a\log(y + \theta)$ ( $a = 18.566, \alpha = 1.719, \text{and } \theta = 10575$ )

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## Appendix B Model results

**Table B1** Percentage changes (%) in production activity inputs and their prices

Variable	Scenario 1	Scenario 2	Scenario 3
<i>Production factor (QVA)</i>			
Agriculture	-0.38	-0.73	-0.02
Fishing	-2.78	-3.41	-13.60
Fish processing	-1.38	-1.84	-4.19
Aquaculture	-5.51	-5.15	-1.49
Other electricity	5.22	5.50	0.06
OWF electricity	50.31	-8.28	0.06
Industry	0.32	-0.13	0.07
Services	-0.26	-0.07	0.02
<i>Production factor price (PVA)</i>			
Agriculture	0.17	0.22	-0.02
Fishing	0.15	0.21	0.99
Fish processing	-0.06	-0.03	0.01
Aquaculture	0.16	0.22	-0.02
Other electricity	0.16	0.21	-0.02
OWF electricity	0.06	0.11	-0.01
Industry	0.01	0.05	0.00
Services	0.03	0.07	0.00
<i>Intermediate input (QINT)</i>			
Agriculture	-0.34	-0.67	-0.03
Fishing	-2.72	-3.30	-13.34
Fish processing	-1.42	-1.87	-4.27
Aquaculture	-5.48	-5.07	-1.48
Other electricity	5.44	6.08	0.06
OWF electricity	50.51	-7.95	0.06
Industry	0.34	-0.08	0.07
Services	-0.25	-0.05	0.02
<i>Intermediate input price (PINT)</i>			
Agriculture	0.04	0.03	-0.01
Fishing	-0.06	-0.16	-0.01
Fish processing	0.09	0.07	0.26
Aquaculture	0.05	-0.07	-0.04
Other electricity	-0.54	-1.58	-0.01
OWF electricity	-0.36	-1.06	-0.01
Industry	-0.03	-0.10	-0.01
Services	0.00	-0.01	0.00

**Table B2** Percentage changes (%) in foreign exchange rate, exports, and imports

Variable	Scenario 1	Scenario 2	Scenario 3
EXR	-0.01	-0.04	0.01
<i>Exports (QE)</i>			
Agriculture	-0.63	-1.09	0.03
Fishing	-2.79	-3.41	-13.74
Fish processing	-1.43	-1.89	-4.31
Aquaculture	-5.55	-5.16	-1.47
Electricity	6.83	10.22	0.11
Industry	0.33	-0.15	0.10
Service	-0.32	-0.23	0.05
<i>Imports (QM)</i>			
Agriculture	0.27	0.20	-0.16
Fishing	-0.85	-1.14	-0.66
Fish processing	-0.17	0.04	-0.02
Aquaculture	-2.74	-2.69	-2.57
Electricity	2.51	-2.34	-0.05
Industry	0.34	0.07	-0.05
Service	-0.14	0.24	-0.03

**Table B3** Percentage changes (%) in household consumption and government consumption (real absorption)

Variable	Scenario 1	Scenario 2	Scenario 3
<i>Household consumption (<math>\sum_h QH_h</math>)</i>			
Agriculture	-0.09	-0.03	0.00
Fishing	-0.23	-0.05	-0.31
Fish processing	-0.20	-0.08	-0.06
Aquaculture	-0.62	-0.11	0.05
Electricity	-0.07	0.41	0.00
Industry	-0.44	-0.23	0.00
Service	-0.47	-0.20	-0.01
<i>Government consumption (QG)</i>			
Agriculture	-0.12	-0.15	0.01
Fishing	-0.22	-0.24	-1.64
Fish processing	-0.08	-0.10	-0.32
Aquaculture	-0.30	-0.24	0.11
Electricity	0.72	2.15	0.01
Industry	0.01	0.01	0.01
Service	-0.03	-0.06	0.00