STRATHCLYDE

DISCUSSION PAPERS IN ECONOMICS

ECONOMIC AND ENVIRONMENTAL IMPACTS OF UK OFFSHORE WIND DEVELOPMENT TO 2029: THE IMPORTANCE OF LOCAL CONTENT

BY

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NO 19-10

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Economic and environmental impacts of UK offshore wind development to 2029: the importance of local content

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JEL: Q40, Q43, Q54

Abstract

The continuing development of the offshore wind sector is an important element of UK energy and industrial policy since it holds the potential of substantial emissions reductions while simultaneously boosting economic activity. A central idea here is that the economic impact of the offshore wind sector can be enhanced by increasing the local content of its inputs. We explore, through simulation of a purpose-built Input-Output model of the UK, the economic and emissions impacts of the likely future development of the UK's offshore wind sector, with a particular emphasis on the importance of local content. We explore six scenarios all of which embed the capacity expansion anticipated by the Sector Deal, but differ in terms of local content – including a set of illustrative simulations considering the possible impact of Brexit on local content. We find that future offshore wind development does indeed generate a "double dividend" in the form of simultaneous and substantial reductions in emissions and improvements in economic activity. It is also the case that, as anticipated, the scale of the economic stimulus arising from offshore wind development is directly and strongly related to the extent of local content.

Keywords: low carbon economy; industrial strategy; supply chain; offshore wind; economic impact; input-output analysis; Brexit.

Acknowledgements: The authors acknowledge funding from the Supergen Wind Hub under EPSRC award EP/L014106/1. Errors and omissions remain the responsibility of the authors.

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1. Introduction

In recent years, UK energy policy has seen significant changes with two key components being to tackle the country's contribution to climate change whilst stimulating the economy. Fundamental to the newly stated energy policy is the reduction of greenhouse gas (GHG) emissions levels with an ambitious target of becoming net zero carbon by 2050 (Committee on Climate Change, 2019). To meet these targets, a number of policies have been introduced to reduce emissions in both the supply and consumption of energy.

To reduce GHG emissions attributable to electricity generation a range of polices are currently in place to stimulate the growth of renewable technologies. Under the EU 2020 targets (European Commission, 2012), the UK has an obligation for 15% of its total energy consumption to be from renewable sources with renewable electricity playing a significant part. The UK government has committed to the steady reduction of coal power generation with closure of all plants by 2025 (UK Government, 2018), with renewable technologies being expected to make up the shortfall from coal closure[2].

A key aspect of recent UK policy towards renewable electricity has been the overhaul of the low-carbon electricity mechanism. Previously, the Renewable Obligation Certificate (ROC) scheme guaranteed renewable electricity generators additional income per MWh on top of the electricity market price. The additional income from ROCs varied with the type of generator[3]. However in 2014 the ROC scheme was replaced with Contracts for Difference (CfD) whereby generators are guaranteed a fixed price per generated MWh, determined through regular auctions for renewable energy capacity. The intention of the CfD is to decrease costs to consumers by lowering the price of electricity through competition, while providing long-term financial stability to project developers (Carbon Brief, 2017)[4].

While the reduction of GHGs is of the upmost importance, the UK Government has stressed that this must not be at the expense of the economy; indeed recently UK industrial policy has set the ambition to simultaneously growing the economy while reducing GHG emissions. As part of the 2017 UK Industrial Strategy (UK Government, 2017) offshore wind was identified as a sector in which investments would bring significant economic growth. Also, the Clean Growth Strategy (BEIS, 2018) focuses on industries which are key to both economic development and the reduction of GHG emission – again offshore wind was identified as being key. From both these strategies the offshore

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[2] Between 2008 and 2017 the electricity generated by coal reduced by 102.5TWh (81.89%) while the generation from renewables grew by 77.5TWh (454.68%) (BEIS,2019)

[3] To encourage the development of technologies, banding was introduced with less mature technologies, such as tidal and wave, received more ROCs per MWh of electricity generated.

[4] The CfD process has seen successful awards to offshore wind projects. At time of writing, some 7.5GW of offshore wind capacity has secured CfDs, for commissioning between 2017 and 2024.

wind sector received a Sector Deal which outlines future plans for growth, sector development ambitions (including skills) and the necessary role for public and private investment (BEIS, 2019b).

With total installed capacity of 8.1GW at the end 2018, and a further 10 GW at various stages of development, the UK is already the European leader in offshore wind energy in terms of actual and planned capacity. As already noted, the ambition of the UK Government is to use this expanding sector to help drive economic growth while aiding in the decarbonisation of the electricity grid; a policy "double dividend" in that one policy (encouragement of offshore wind) has a beneficial impact on two key policy goals, which have traditionally been regarded as conflicting.

The economic impacts on the UK of future offshore wind developments will be affected by the level of capacity deployed, but also critically by the extent to which inputs to projects are sourced from UK firms, i.e. the degree of "local content".

Local content (for the UK) has been defined as follows (BVG, 2015):

> *"UK content is the percentage of the total undiscounted expenditure by the Wind Farm Asset Owner on a Wind Farm that is ultimately spent through Contracts awarded to companies operating in the UK. It excludes the value of Contracts to UK companies that is spent on Subcontracts to companies not operating in the UK. It includes the value of Contracts to non-UK companies that is spent on Subcontracts to companies operating in the UK"*

BVG Associates (2015) outlined a methodology to standardise the calculation of local content of UK offshore wind developments[5]. In recent years, the UK has made significant progress towards meeting this target with several offshore wind farms in development expected to exceed 50% local content (e.g. East Anglia 1). Due to the complex nature of offshore wind developments, with the need for large specialised manufacturing, a considerable amount of UK local content is concentrated on the development and installation stages of projects. However, this is beginning to change with established manufacturers investing in plants in the UK (such as Siemens in Hull). Naturally, a 100% UK content target for offshore wind projects seems unrealistic currently as this would reduce competitiveness (since this could only be achieved through substitution of higher priced domestic inputs for imported

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[5] In this BVG approach, "filtering" is applied whereby the measurement of local content for any contract above the £10 million threshold is the responsibility of subcontractors. For example, the process beings with the large tier 1 contracts, if the contract is valued greater than £10 million (which they will most likely be) then the responsibility of measuring local content falls on the tier 1 suppliers who then report back to the asset owner. If the tier 1 contract is below £10 million then the asset owner is responsible for the local content of any contract[5]. While this methodology standardises the calculation of local content, several critics have noted that the £10million threshold (especially for higher tier contacts) is too large, leading to inaccurate measurements.

inputs) and increase overall project costs. There has therefore been much debate on the 'ideal' level of local content for offshore wind projects and how this may be achieved. There are several policy measures which can be implemented to support an increase in local content including the imposition of: local content requirements; financial/tax incentives and favourable customs duties (Lewis & Wiser, 2007). One of the aspirations of the recent Sector Deal is to increase UK content, aiming for 60% by 2030 (BEIS, 2019b). While it is a policy objective to grow UK content, with the intention that this will increase the impact of developments on the UK economy, but also that a UK offshore wind sector with experienced supply chain can export skills and goods to service the European and world offshore wind markets.

The purpose of this paper is to explore the potential economic and environmental impact on the UK of developments in UK offshore wind capacity between 2019 and 2029. In total, we investigate six scenarios: two based on current local content potential; and a further two where the 60% target is achieved. In addition, Brexit – the UK's departure from the European Union - could have many effects. One consequence for the offshore wind sector would be the increased costs of importing goods/services to/from European markets. Currently, UK developments often have a significant portion of inputs coming from European suppliers. In two further scenarios, we look at the potential additional effects of Brexit on the scale of local content in future offshore wind developments. Varying the scale of local content in each scenario is similar to how sensitivity around point estimates of local content is handled in Williams et al. (2008).

In this paper, we use an Input-Output (IO) economic modelling framework. In carrying out the modelling we first calculate, using information from the offshore wind sector deal, the expected capacity increase from 2019 to 2029. From this, we estimate the component cost and breakdown for each MW of installed capacity. We then detail the level of local content of each cost component for each scenario. Using the offshore wind bridge matrix that links cost components to the industrial classification used in our model, we convert yearly component expenditures (accounting for local content) into a format in which they can be introduced into an IO model as demand 'shocks'.

IO modelling has been used extensively to investigate the potential economic impacts arising from the move towards a greener energy network, with a wide range of technologies and nations (and regions) being modelled. Jenniches (2018) analyses 54 publications from the UK, USA, Spain, Germany, and Austria, which investigate the economic impacts of renewable energy developments, and finds IO to be a widely employed methodology, and wind energy to be the focus of a large number of papers. In the USA the NREL JEDI[6] model has been used extensively to explore the economic impacts from wind energy, both offshore (e.g. Tegan et al., 2015) and onshore (e.g. Slattery et al., 2011). Both IO and computable general equilibrium (CGE) modelling are used in Allan et al. (2014) to investigate the potential economic impacts of an increase in Scottish marine energy (wave and tidal) on the Scottish economy, while Fanning et al. (2014) and Bere et al. (2015) use IO methodologies to look at wave/tidal and small hydro in Wales respectively. In these previous papers are based on the standard System of National Accounts (SNA) framework, containing a single electricity sector.

Our analysis differs from previous studies as the IO database we use disaggregates the electricity sector to separately identify the offshore wind sector. Given the heterogeneity of the electricity sector, this disaggregation promises significantly improved estimates of impacts, since it more accurately tracks the impacts of expenditures on the construction and operational phases of new windfarm investments. In addition to exploring the economic impacts, we also analyse the emissions impacts resulting from these offshore wind developments. In doing so, we set out the extent to which the UK could see reductions in emissions alongside increases in the contribution to the generation mix from offshore wind technologies.

This paper proceeds as follows: Section 2 outlines the IO methodology, and our contribution relative to previous studies employing this approach. Section 3 outlines our simulation strategy, while Section 4 then presents and discusses the results of the analysis across the six scenarios considered. Brief conclusions are presented in Section 5.

2. Input-Output methodology and Data

2.1 Input-Output (IO) method

IO models are based on a set of simultaneous equations that record the sectoral linkages within an economy, producing the Leontief inverse matrix (Miller & Blair, 2009). IO models are calibrated using the information from national (or regional) IO tables. These are a set of economic accounts which record the inter-industrial sales and purchases within an economy, with the concept of double entry bookkeeping whereby every sale must have a buyer and every purchase is the result of a sale. These tables provide a snapshot of the economy within an area for a set period of time (normally a year) and represent the monetary value of all these transactions.

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[6] JEDI are a set of Input-output models developed by the National Renewable Energy Laboratory (NREL) to measure the economic impacts, both national and state wide, resulting from the construction and operation of power plants.

Describing the output of individual sectors within an economy, we can specify:

$$X_1 = a_{11}X_1 + a_{12}X_2 + .. + a_{1n}X_n + f_1 \quad (1)$$

$$X_2 = a_{21}X_1 + a_{22}X_2 + .. + a_{2n}X_n + f_2 \quad (2)$$

……………………………………

$$X_n = a_{n1}X_1 + a_{n2}X_2 + .. + a_{nn}X_n + f_n \; (3)$$

Where X_i is the output of sector i and a_{ij} coefficients represents the output of sector i needed to produce one unit of output of sector j. F_i is the sales of sector i to final demand. In matrix notation this can be represented by:

$$\boldsymbol{X} = \boldsymbol{AX} + \boldsymbol{F} \qquad (4)$$

which gives the following solution for X:

$$\boldsymbol{X} = (\boldsymbol{I} - \boldsymbol{A})^{-\boldsymbol{1}}\boldsymbol{F} \qquad (5)$$

$$\Delta\boldsymbol{X} = (\boldsymbol{I} - \boldsymbol{A})^{-\boldsymbol{1}}\Delta\boldsymbol{F} \qquad (6)$$

I is an identity matrix, with $(\boldsymbol{I} - \boldsymbol{A})^{-\boldsymbol{1}}$ the Leontief inverse matrix. Equation 6 can be used to explore the impacts on aggregate and sectoral outputs of changes in (exogenous) final demand. This "demand-driven" IO model can be used to estimate the effect of demand changes on different economic variables - including output, employment and GVA – through the use of multipliers[7].

There are two main variations of the demand driven IO model (i.e. Type I and Type II), which differ in their treatment of households. For Type I the household sector is treated as exogenous to the model and as such is not included in the **A** matrix, but within F. A Type I multiplier captures the direct and indirect change resulting from a unit change in final demand for the output of a sector.

Type II demand-driven models also measure the direct and indirect effects along with a third effect, the 'induced effect'. An increase in final demand requires some increase in labour input, reflected in the increased payment to compensation of employees. This in turn will generate additional increases in demand – due the workforce having an increased level of disposable income to spend - and thus output. This is known as the induced effect and is calculated by 'closing' the IO model to endogenise

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[7] By calculating coefficients linking sectoral values for, e.g. employment, value added, emissions, to sectoral output we can explore the consequences on a range of indicators of the change in demand. For example, where m_i represents the employment-output coefficient (jobs per unit of output in sector i) we can calculate the change in employment from a change in demand as $\Delta\boldsymbol{M} = \boldsymbol{m_i}(\boldsymbol{I} - \boldsymbol{A})^{-\boldsymbol{1}}\Delta\boldsymbol{F}$, where elements within M reveal the impacts on employment at the sectoral level.

household consumption. This involves expanding the **A** matrix to add a row and column representing household labour and consumption (Miller & Blair, 2009).

Demand-driven IO models make two key assumptions. The first is the assumption of fixed technical coefficients whereby output is always generated through the same share of sectoral inputs: IO models do not allow for substitution effects. Secondly, in demand-driven IO models the supply side is assumed to be completely passive with changes in economic activity determined entirely by changes in demand. This assumes that the increase in demand is always met without increasing pressure on the prices, wages or labour supply; there are no resource constraints.

2.2 IO data

For our analyses, we use a set of 2010 IO tables for the UK as reported in Allan et al (2019a,b). These are the latest data available at the time of writing. The 2010 IO table is a symmetric IxI IO table with 98 industries defined at the Standard Industrial Classification (SIC) 2007, which are further expanded with nine electricity generation sectors: Coal, Gas & Oil, Nuclear, Onshore Wind, Offshore Wind, Pumped, Hydro, Biomass, and Other. To match the information from the offshore wind matrix of cost components, we aggregate the full 98 sector table to 25 sectors, detailed in Appendix A.

Data in the IO tables also record socioeconomic characteristics in two dimensions. First, we link two indicators to sectoral output, so that we can explore the activity supported in more than purely economic (monetary) terms (see footnote 7). These are sectoral employment (in Full-time equivalent, FTEs) and Gross Value Added (GVA). Employment is further broken down in the IO table, providing greater depth to this indicator by reporting (for each sector) employment across nine occupation categories, as given by Standard Occupational Classifications (SOC).[8] We aggregate these to three categories that we term “High”, “Medium” and “Low” skilled for presentation purposes, following a standard approach of aggregation.[9]

Standard IO tables only report a single a single sector covering the electricity sector (SIC 35). As noted earlier, this sector contains firms mapped to the activities within this SIC, which include distinct elements – electricity generation (i.e. the production of electricity), transmission and distribution, as well as retail and trading. These activities are very distinct, meaning that the published (aggregate)

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[8] See Ross (2017) for more detail on skill disaggregation.

[9] The nine categories are 1) “Managers and Senior Officials”, 2) “Professional Occupations”, 3) “Associate Professional and Technical”, 4) “Administrative and Secretarial”, 5) “Skilled trades occupations”, 6) “Personal service occupations”, 7) “Sales and Customer Service Occupations”, 8) “Process, plant and machine operatives” and 9) “Elementary Occupations”. Categories 1 to 3 are classed in our later analysis as “High skill”, with categories 4 to 8 and 9 respectively termed, “Medium skill” and “Low skill”. More details on these skills are given in Ross (2017).

electricity sector is unlikely to represent the purchases and sales pattern for any one of these activities. Second, the nature of generation technologies activities means that there will be heterogeneity among the (backward) linkages of each technology. Third, the forward linkages of each technology will be identical – each will sell electricity onwards to retail and consumption uses across the economy. The generation mix therefore will have major implications for the pattern of the purchases by the electricity sector in the national accounts. Furthermore, the activities of electricity retail and trading – counted as part of the electricity sector – comprise a major element of the employment within the sector, and so require disaggregation. Finally, disaggregation of the electricity sector is essential, as from the offshore wind bridge matrix (Appendix B), an increase in capacity directly impacts the offshore wind sector.

The data given in Allan et al. (2019a,b) use information on plant-level production and market price by half-hourly time-step based on the framework developed in Connolly (2018). We can therefore capture the timing and economic value of production by technology in identifying the revenues for each technology. This method can take into account that some technologies produce only when demand (and therefore price) is high, while others are unable to alter their outputs in response to market behaviour. One example highlights the usefulness of this "bottom-up" estimation of revenues. By using disaggregated data from Allan et al. (2019a,b) on electricity generation by technologies in our IO framework, we can separately identify the activities which are supported by generation from offshore wind technologies from those which are due to the addition of new offshore wind capacity.

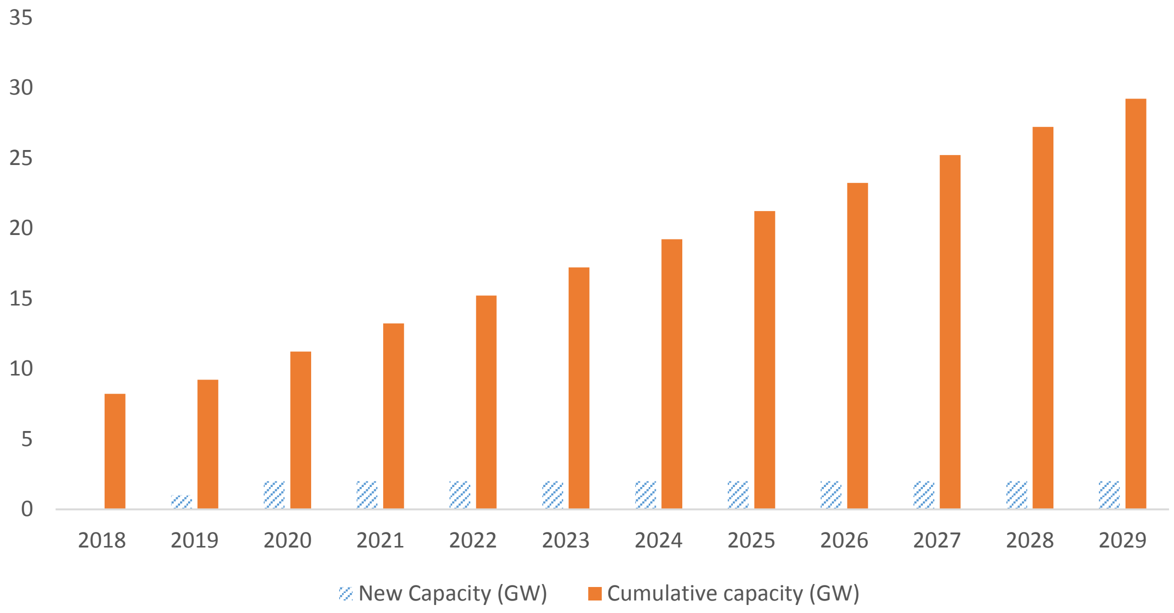
3. Simulation Strategy

Modelling the impact of developments in UK offshore wind capacity under our six scenarios requires a number of steps, which we detail in this section. In summary, we first calculate, using information from the offshore wind sector deal, the expected capacity increase from 2019 to 2029. From this, we estimate the component cost and breakdown for each MW of installed capacity. We then estimate the level of local content of each cost component, using the offshore wind bridge matrix that links cost components to the industrial classification used in our model. We convert yearly component expenditures - accounting for local content, and so with varying expenditure under each category for each scenario – into a set of demand disturbances which are then introduced into an IO model as demand 'shocks'.

3.1 *Capacity projections*

As outlined in the offshore Sector Deal, the UK has a clear vision significantly to grow offshore wind capacity by 2030. For all the scenarios in this paper, we assume that the capacity follows the sector deal whereby throughout the 2020s 2GW of capacity is added to the grid each year. This is essentially a linear increase between current capacity and the target for 2029. Figure 1 outlines the increment to capacity each year as well as cumulative capacity.

Figure 1*: New and cumulative UK offshore wind capacity 2019-2029 implied by the sector deal*



Source: Authors calculations, based on BEIS (2019a), BEIS (2019c) and own extrapolation.

3.2 *Expenditures*

Beginning with capital costs for offshore wind, expenditures on devices can be assigned to a number of different categories: Development and project management; Nacelle and hub; Blades; Cables; Onshore cables; Foundation and substructure; Substation; Foundation installation and commissioning; Cable installation and commissioning; Turbine installation and commissioning; Onshore cable installation and commissioning; Substation installation and commissioning, expenditures. The breakdown of these costs varies depending on a number of factors with location and technology being key. For the cost breakdown of UK offshore windfarms we consult the information available from The Crown Estate (2010) and BVG (2010). We estimate turbine costs to be around 39% of CAPEX which is in line with the other studies in the literature (Higgins & Foley, 2013). Overall we assume a CAPEX cost per MW of £2.1 million (Wind Europe, 2018)

Along with the cost breakdown there is also a timing issue as capital costs are typically distributed over a number of years. Through investigating several EIA reports[10] we estimate that a full development of a ‘generic’ UK farm, from pre-development to full installation and operation takes six years, with the capital expenditures allocation across years summarised in Table 1.

***Table 1**: Yearly breakdown of CAPEX costs, in %*

Year 1 (operation minus 6)	Year 2	Year 3	Year 4	Year 5	Year 6 (operation minus 1)
0.37	1.82	16.43	32.12	27.13	22.11

We also have to estimate operations and maintenance (O&M) costs which support wind farms during their lifetime operation to ensure optimum output. In each of the simulations we assume that each MW of capacity will be operational for 25 years at a cost of £66,229 per MW per year (Carrol et al., 2017).

3.3 Allocation of spending to industrial sector

Each of the capital and O&M expenditures are allocated to an appropriate SIC code using a bridge matrix reported in Appendix B. This is necessary because the IO table and model employ this official UK classification of sectors. Note that the direct impact of installation is heavily concentrated in just two sectors, Iron and steel and Transport.

3.4 Local content

With the focus of this paper on the economic impacts of local content changes we explore six scenarios with different local content assumptions, but same increase in capacity. The first two scenarios (2019

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[10] Arcus Renewable Energy Consulting ltd (2012), Repol and EDP renewables (2014), Mainstream Renewable Power (2012), Seagreen Wind Energy (2012) , Moray Offshore Renewabls Ltd (2013)

low and 2019 high[11]) are based on publicly available information for the East Anglia wind farm, outlined in Table 2.

***Table 2**: Local content of different components of offshore windfarms, in %.*

Components	2019 Low content	2019 High content
Pre development costs	80	90
Turbine supply	19	29
Turbine Installation	16	26
Foundation design	50	50
Foundation and pile fabrication	25	53
Foundation installation	5	10
Array cable installation	14	28
Array cable supply	16	26
Grid Transmission	13	29
CAPEX (Weighed average)	22	35
OPEX	71	80
Lifetime total	40	52

Source: Scottish Renewables (2019)

In the first scenario, there is an overall a lifetime local content of 40%, there is little manufacturing activity (turbine/array/foundation) cable supply. CAPEX activity that does have significant UK content is Foundation design reflecting the fact that UK expertise in designing offshore oil platforms can be transferred to wind turbine foundation.

Under the second scenario with a more “active” attempt to increase local content within the supply chain, current offshore wind farms have the potential for an overall UK content increase of 12 percentage points to 52%. In this scenario, there are significant increases in UK content for the electrical infrastructure and foundation fabrication – with more than double previous content. Rather than based on current developments, we make estimates on the local content for the other four scenarios, outlined in Table 3.

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[11] In the low content scenario the developer is passive in its procurement process, while in the high content case the developer is seen as ‘active’ with its supply chain to maximise the participation of UK companies.

Both scenarios 3 and 4 use 2019 high content assumptions as a baseline. In scenario 3 we assume that the 60% content target is met through the turbine supply category[12] whereas scenario 4 assumes that the target is achieved through installation activities.

***Table 3**: Simulation scenarios in brief*

Scenario	Local content total	Description
2019 low (Scenario 1)	40%	2019 local content with developer passive approach to procurement
2019 high (Scenario 2)	*52%*	2019 local content with developer active approach to procurement
Increased content manufacturing (Scenario 3)	*60%*	Meet 60% target with focus on installation of components
Increased content installation (Scenario 4)	60%	Meet 60% target with focus on supply of components
Brexit low (Scenario 5)	30%	Brexit leads to relocation out of UK. Local content of activities decrease.
Brexit high (Scenario 6)	70%	Brexit leads to relocation into UK. Local content of activities increases.

Scenarios 5 and 6 relate to the potential impact of Brexit through one of the possible impacts for the offshore wind developments. While the precise timing, shape and implications that the UK leaving the EU will have is not known at time of writing, we can speculate that it will impact on UK energy activities in a number of ways. Most critically, are any implications of Brexit for the stated policy objectives around energy and low carbon policy. Second are the consequences for economic activity, and government revenues, which will be reflected in the scope for government to expand financial support for renewable energy technologies. As a more mature technology, offshore wind may conversely benefit from reduced funding for technological development of renewable energy.

These two factors combine to create what is known as the Home Market Effect (Krugman, 1980): returns to scale mean that the industry will agglomerate, while trade costs mean that this agglomeration will occur in the largest market (the Home market). Brexit will increase trade costs, and the UK is a very significant market for the offshore wind industry. The Brexit related increase in trade costs could incentivise the location of the supply chain within the UK to avoid trade costs associated

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[12] Turbine manufacturers have already begun to invest heavily in the UK.

with imports from the EU. Alternatively, the Brexit related increase in trade costs could incentivise the location of the supply chain in the rest of the EU if this is deemed to be the most important market. Appendix C sets out how we might formulate a simple model to explore the trade-offs which could exist.

Our two scenarios cover alternative possibilities coming from Brexit. In the first scenario, labelled ‘Brexit low’, we assume Brexit leads to multinational companies moving operation from the UK resulting in lower local content for offshore wind. In the second Brexit scenario (‘Brexit high’) the assumption made is that developers use a higher level of local content to avoid trade costs associated with imports from the EU.

3.5 Varying the A-matrix IO model and carbon emissions

As identified previously a key objective of increasing offshore wind capacity is to reduce greenhouse gas emissions through the replacement of fossil fuel generation. In the standard IO framework outlined in Section 2.1 this replacement of capacity would not be captured due to the static **A** matrix. In our modelling, we adapt the IO framework by introducing a time varying **A** matrix in which the increase in offshore wind capacity replaces fossil fuel generation, which is particularly useful for the calculation of emission impacts.

The first stage, in the time-varying **A** matrix method, is to estimate potential power output (in MWh) arising from the increase in offshore wind capacity (in MW). We use input information from BEIS (2019c) and develop a power-to-capacity coefficient for UK offshore wind.

$$pf = \frac{Output\ (GWh)}{Capacity\ (MW)}[13] \qquad (7)$$

Applying this power coefficient to the capacity information presented in Figure 1 generates the level of UK electrical output, per year and cumulative, that is replaced by offshore wind. The assumption made here is that the offshore wind capacity will initially replace coal generation then gas, in line with UK energy policy (UK Government, 2018). Using this information we adapt the offshore wind and fossil fuel generation coefficients within the **A** matrix as:

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[13] We take power coefficient as the average over the last 5 years

$$a_{fossil,eled}(T) = a_{fossil,eled}(2010) * \frac{cumulative\ offshore\ wind\ output\ (MWh)\ (T)}{fossil\ fuel\ generation\ (2010)} \quad (8)$$

$$a_{offshoreW,eled}(T) = a_{offshoreW,eled}(2010) + a_{fossil,eled}(2010) - a_{fossil,eled}(T) \quad (9)$$

$$a_{offshoreW,eled}(T) + a_{fossil,eled}(T) = a_{offshoreW,eled}(2010) + a_{fossil,eled}(2010) \quad (10)$$

With equation (8) the *a* coefficient of inputs to the electricity distribution sector (*eled*) from the fossil fuel at time *t* is determined by scaling the 2010 *a* coefficient by the ratio of offshore wind generation at time *t* and fossil fuel generation in 2010. The increase the *a* coefficient of inputs to the electricity distribution sector from the offshore wind (*offshoreW)* at time *t* is the difference between the fossil fuel *a* coefficient in 2010 and time *t*. Equation (10) ensures overall the totals of the **A** matrix remain unchanged, with only the offshore wind and fossil fuel elements updating. These are then introduced at each time-step of the modelling in Equation 6.

A motivation for using the time-varying **A** matrix model was to account for the change in emissions with an increase in offshore wind capacity. In this paper, we recognise two sources of changes in carbon emissions attributable to the increase in offshore wind. First, emissions are generated throughout the economy by the construction and operation of offshore wind capacity. Second, however, the increase in offshore wind capacity replaces fossil fuel generation, impacting the electricity mix and so reducing emissions; indeed this is a key part of the motivation for policies encouraging the substitution in favour of renewables. We estimate the change in emissions arising from both sources.

Using the fuel use by economic sector database (ONS. 2018) we calculate sectoral emissions coefficients for the three primary fuel types (coal, gas, oil) according to Allan et al. (2018). We then use these emission coefficients to estimate the total CO_2e resulting from the development and operation of UK offshore wind using;

$$\Delta E_f = \sum_i^n \Delta X_i * F_f \quad (11)$$

$$\Delta Etotal = \sum_f^n \Delta E_f \quad (12)$$

Where ΔX_i is the change in the output of sector i attributable to the increase in wind farm capacity and operations and maintenance activity; F_f the emissions factor of fuel f; E_f the emissions of fuel f and $Etotal$ the total emissions. In this paper, Equation 11 is applied to both time-varying and non-time-varying methodologies.

3. Results/Discussion

3.1 Economic impacts

Table 4a reports the economic impacts of increasing UK offshore wind capacity to 2029 with 2019 low local content assumptions, separated into 'direct', 'indirect' and 'induced' effects, as well as two distinct time periods. The first column, labelled 2014-2029, is the construction stage during which all capacity is constructed, while the second column - labelled 2030-2054 - is the operational stage of the wind farms (i.e. in which no further construction/installations is assumed to take place).

***Table 4a**: Potential cumulative economic impacts of UK offshore wind to 2029 with 2019 low local content (scenario 1)* (Non-discounted)

	2014-2029	2030-2054	Total
Direct			
Output	13,798.6	19,011.7	32,810.3
GVA	4,814.3	7,925.3	12,739.6
Employment	66,936	76,658	143,594
Indirect			
Output	10,035.2	15,814.1	25,849.3
GVA	4,432.5	7,178.8	11,611.2
Employment	75,724	126,229	201,954
Induced			
Output	15,967.9	22,073.3	38,041.2
GVA	4,135.0	5,716.2	9,851.2
Employment	77,201	106,724	183,924
Total			
Output	39,801.7	56,899.1	96,700.8
GVA	13,381.8	20,820.3	34,202.0
Employment	219,861	309,611	529,472

Note: Output in £ million, GVA in £ million, and Employment in FTE

Table 4a illustrates that cumulatively the economic impacts are larger during the operational stage of the project than the construction stage, due to the larger spending (direct) occurring at the operational stage[14]. There is larger average investment during the construction stage in this scenario, but the operational stage is much longer, thus the higher direct expenditure. Also we find from Table 4a that the sum of indirect & induced impacts – that occur through the UK offshore wind supply chain and increase in employment- are much larger than the direct effects, with the combination of indirect & induced impacts accounting for 63% and 73% of the cumulative total impacts on GVA and employment totals respectively.

In Table 4b we report the economic impacts found in Table 4a in present value terms (i.e. using a discount factor of 3% to calculate the value of impacts "today"). With the operational stage occurring much further in the future, we find that (for scenario 1) with discounting, the construction stage impacts are now larger than at the operational stage. In addition, we find that for output and employment during the construction stage, induced impacts are larger than direct.

Table 5 summarises the cumulative (i.e. the sum of all economic impacts across all time periods, in present value terms) aggregated results of our simulations[15]. As would be expected, the macroeconomic impacts increase with the proportion of local content. This occurs as a larger proportion of spend is on outputs produced by UK-based companies. Comparing the two 2019 scenarios (Scenarios 1 and 2), for example, we find that with a local content of 40% the expected increase in GVA and employment of £19.9 billion and 311,810 FTEs respectively. With 12% increase in local content to 52% total the Type II GVA impacts increases to £26 billion and employment 414,150 FTEs.

Although both Scenarios 3 and 4 have 60% local content, the results differ slightly – though both have significantly greater impact than the previous two scenarios. If the increase in content is focused on manufacturing of components (Scenario 3) we find there is a cumulative GVA increase of £28.9 billion and employment increase of 465,121 FTEs. However if the content is focused on installation of components we find that the macroeconomic impacts are higher, with GVA increasing to 29.8 million and employment 478,250 FTEs, £877 million and 13,134 FTEs larger compared with Scenario 3. Recall, there has been no change in the overall scale of offshore wind capacity between these scenarios; these differences in GVA and employment occur as the sectors involved in the installation of wind farm components have a higher GVA- and labour-intensity than those involved in manufacturing.

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[14] In other Scenarios, this may not necessary be the case for all scenarios as an increase in local content at the CAPEX stage will increase capital investment at the construction stage

[15] We only focus on the Type II results, which reflect the combination of direct, indirect and induced changes. See Emonts-Holley et al. (2015) for a detailed discussion of calculation methods of Type II multipliers.

***Table 4b**: Potential cumulative economic impacts of UK offshore wind to 2029 with 2019 low local content (scenario 1)* (discounted)

	2014-2029	2030-2054	Total
Direct			
Output	10,957.7	9,472.2	20,430.0
GVA	3,845.2	3,948.6	7,793.8
Employment	53,162	38,193	91,355
Indirect			
Output	6,893.9	7,021.7	13,915.5
GVA	3,056.7	3,204.8	6,261.5
Employment	54,010	57,896	111,907
Induced			
Output	12,001.0	10,454.2	22,455.2
GVA	3,107.8	2,707.3	5,815.0
Employment	58,022	50,546	108,567
Total			
Output	29,852.6	26,948.1	56,800.7
GVA	10,009.7	9,860.7	19,870.4
Employment	165,194	146,635	311,829

Note: Output in £ million, GVA in £ million, and Employment in FTE.

***Table 5**: Summary cumulative results for all six simulations, Type II (present value)*

	2019 low (Scenario 1)	2019 high (Scenario 2)	Increased content manufacturing (Scenario 3)	Increased content installation (Scenario 4)	Brexit low (Scenario 5)	Brexit high (Scenario 6)
Output	56,801	75,999	85,891	87,027	40,418	101,882
GVA	19,870	25,998	28,876	29,753	14,291	34,405
Total Employment	311,815	414,150	465,121	478,255	224,492	556,390
- High skill	132,439	174,608	195,041	200,568	95,661	232,756
- Medium skill	139,659	187,239	211,619	217,980	100,093	254,187
- Low Skill	39,717	52,303	58,461	59,706	28,738	69,447

Note: Output in £ million, GVA in £ million, and Employment in FTE.

The final two scenarios relate to the two scenarios motivatied around Brexit’s impacts on local (i.e. UK) content in the offshore wind sector. In the first Scenario (‘Brexit low’) we assume Brexit leading to multinational companies moving operation from the UK resulting in lower local content for offshore wind. In the second Brexit scenario ('Brexit high'), the assumption is made that developers being use a higher level of local content to avoid tariffs. From Table 5 we find that in the 'Brexit low' the economic impacts are the lowest out of all six scenarios with an output £40.4 billion, GVA £14.3 billion and employment of 224,490 FTEs. In the 'Brexit high' case where there is an influx of firms to the UK, the economic impacts are the largest with an increase in an output of £101.8 billion, GVA £34.4 billion and employment of 556,390 FTEs

The IO framework allows for separation of employment by skill level (high, medium, low). We find that both current content scenarios favour high skilled labour. Scenario 1 has both the largest proportion of high skill (42 %) and low skill (13 %) employment, indicating the lowest proportion of medium skill employment at 45% of total. Scenario 2 has a slightly lower high skill employment proportion of (42%) than scenario 1 but has lower low skilled employment at 13 %.Comparing Scenarios 3 and 4 we find that for both the proportion of high skill employment is the same at 42%, however there are difference in medium and low skill employment proportions. Medium skilled employment represents 45.58% of total in Scenario 3 compared with 45.50% in Scenario 4, indicating that employment supported by growing UK content through increasing wind farm manufacturing sector jobs are (marginally) lower skilled than when local content is increased in installation activities.

Comparing Scenarios 3 and 4 we find that for both the proportion of high skill employment is the same at 42%, however there are difference in medium and low skill employment proportions. Medium skilled employment represents 45.50% of total in Scenario 3 compared with 45.58% in Scenario 4, indicating that wind farm manufacturing sector jobs are slightly lower skilled than installation.

For the Brexit scenarios, the lower content has a higher level of high skilled employment that with the Brexit high scenario – 42.61% compared with 41.83. However the there is also a higher level of low skilled employment, 13% and 12% for the Brexit low and high scenarios respectively.

We also report, in Figure 2, the annual impacts on output and GVA for each of the four scenarios over the period from 2019 to 2032. Figure 2 illustrates that the general distribution of impacts across time is the same for each scenario; they differ only in terms of their scale. From 2019 to 2025 we find there is a steady increase in output and GVA, occurring as there is increasing capacity in development with peak output and GVA impacts being reached in 2026. This peak occurs as, from Table 1, a large proportion of capacity is in the construction stage (years 2-6) at this time. After 2026 the impacts steadily decline as the CAPEX stage is coming to an end in 2029 with the installation of the last additional capacity. From 2030 onwards, as we reach the stage in which only O&M expenditures are incurred, we find that the impacts are constant as the O&M cost per MW per year is kept constant. At year 2045, due to the capacity beginning to be decommissioned, the GVA and output impacts start to gradually decrease until 2054 when the last of the operational capacity lifetime ends.

In addition to impacts on aggregate economic activity and employment, the IO model generates estimates of sectoral impacts. Figure 3 displays the changes in sectoral Type II GVA associated with each of the modelled scenarios for the peak year, 2026.

The sectors which benefit the most from the development of UK offshore wind capacity are: services, other transport, manufacturing, construction and the offshore wind sector itself. The Service and the Other Manufacturing sectors not only benefit from a direct demand disturbance but also enjoy very high linkages with the other sectors directly stimulated, notably the Iron and Steel sector and Non-ferrous Metals sector (which receive a large direct increase in demand in all of cases analysed here).

***Figure 2**: Output and GVA timing impacts, in £million*

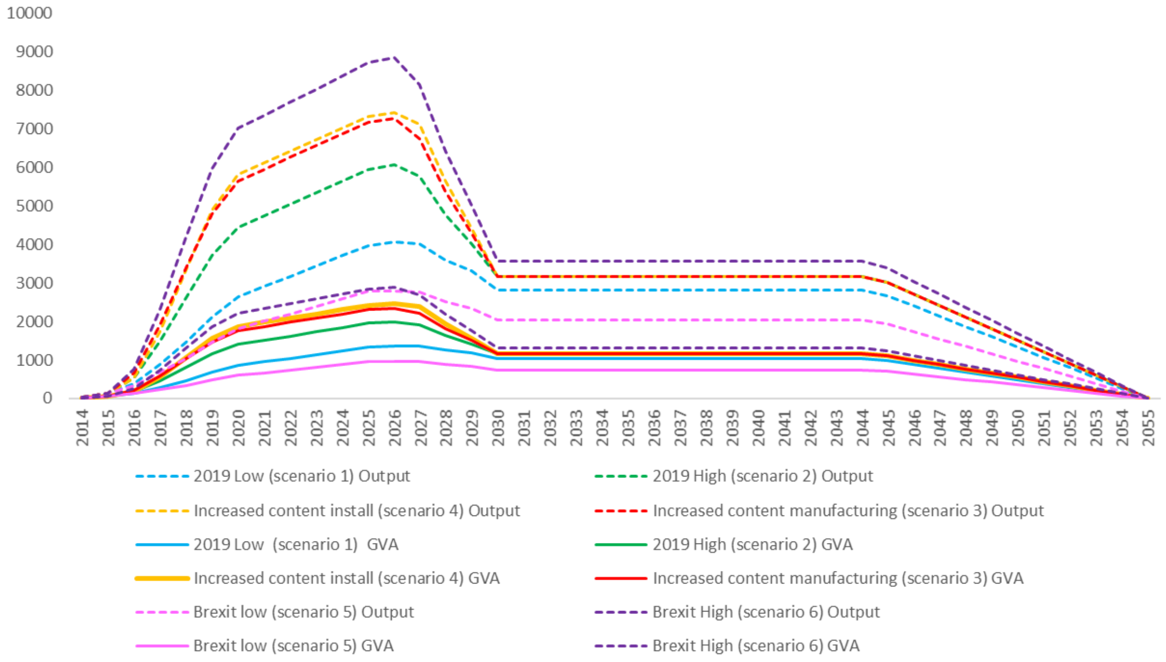
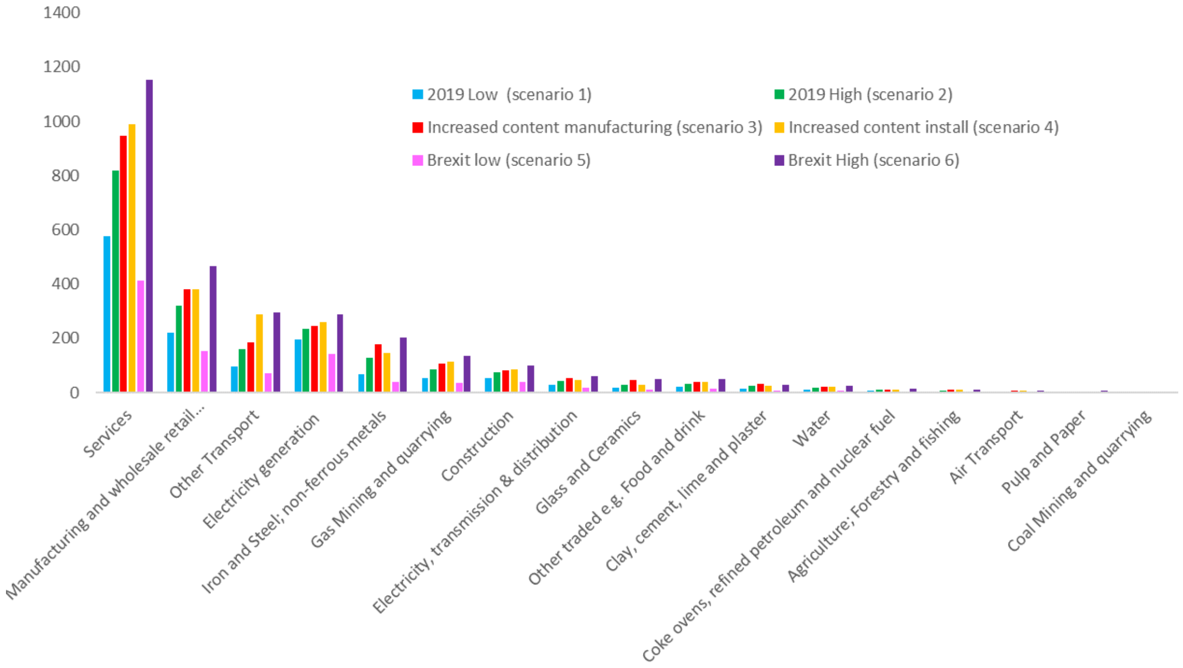


***Figure 3**: Sectoral GVA results for 2026, in £million*



3.2 Environmental impacts

In addition to the macroeconomic impacts of the increase in UK offshore wind capacity, we explore the potential environmental impacts through the associated changes in CO_2e. Table 7 shows the cumulative emissions resulting from the construction and operation of UK offshore wind capacity to 2029. The first column provides estimates of the increase in emissions associated with the construction and operation of the increased wind capacity using the 2010 **A** matrix. The second column provides estimates of the emissions associated with the construction and operation of the increased wind capacity with the time-varying **A** matrix methodology. The third and final column provides estimates of the emissions that are saved as a consequence of the displacement of fossil fuel generation.

As would be expected, the increase in UK offshore wind local content leads to an increase in UK territorial carbon emissions due to the associated increase in demand throughout the economy. We find that the using the base modelling framework results in larger construction emissions, as would be expected as there is still large coal generation. However when using the time varying **A** matrix, accounting for offshore wind replacing fossil fuel generation, we find significant reduction in the construction emissions.

***Table 7**: Cumulative changes in emissions resulting from the construction of UK offshore wind, 2019 to 2054, in Mt CO_2e*

	2010 Base construction	Time-Varying A matrix construction	Total replacement
2019 low (scenario 1)	26,787	23,432	-645,722
2019 high (scenario 2)	40,888	36,295	-632,859
Increased content manufacturing(scenario 3)	48,382	42,982	-626,172
Increased content installation (scenario 4)	56,837	51,997	-617,158
Brexit low (scenario 5)	18,660	16,357	-652,797
Brexit high (scenario 6)	63,763	57,742	-611,412

Overall, we find in all scenarios, over the lifetime of the projects, substantial carbon emission replacements - of between 611,410 and 652,790 Mt CO_2e – which accounts for more than a year worth of current overall UK carbon emissions (BEIS 2019d). Comparing Scenarios 3 and 4, where local content increase to 60%, we find that if the increase in local content occurs through the instillation processes then this would lead to greater territorial emissions than if the focus was on manufacturing (because the former is associated with the greater stimulus to economic activity). This occurs as installation relies heavily on transport sectors which are oil-intensive activities.

5. Conclusions

UK energy policy statements on reducing emissions has been given added urgency by the Government's recent commitment to net zero carbon emissions by 2050. At the same time, there has also been increasing emphasis that this reduction in emissions should be achieved in a way that benefits the economy. The continuing development of the offshore wind sector is regarded as an important element of UK energy policy since it holds the promise of substantial emissions reductions while simultaneously boosting economic activity. This represents a policy "double dividend" in that two key policy objectives, often thought to be conflicting, are simultaneously improved by expanding the offshore wind sector.

The potential contribution of offshore wind has been recognised by the recent UK Industrial and Clean Growth strategies, in the form of a sector deal. A central idea here is that the economic impact of the offshore wind sector can be further enhanced by increasing the local content of its inputs, and through increased export activity linked to sector developments in the rest of the world. In this paper we explore, through simulation of a purpose-built input-output model of the UK, the economic and emissions impacts of the likely future development of the UK's offshore wind sector, with a particular emphasis on the importance of local content.

Our model simulations explore the economic and emissions impacts of a number of possible alternative futures for offshore wind. To highlight its importance we explore six scenarios all of which embed the capacity expansion anticipated by the sector deal, but differ in terms of local content. Two of these are based on publicly available information for the East Anglia windfarm. Even on the local content assumption implied by a developer with a comparatively passive approach to procurement, there are substantial GVA and employment effects (with cumulative effects on value added of over £19 billion and employment of over 310,000 full time equivalents). However, under a more pro-active procurement policy that raises average domestic content from 40% to 52% the cumulative economic impacts are increased significantly (to £26 billion and over 410,000 FTEs).

Two further simulations explore alternative ways in which the sector might meet the 60% sector deal target for domestic content. Naturally, successful achievement of the 60% target further augments the economic impacts, to over £28 billion GVA and employment of over 465,000 in both cases. However, it transpires that achieving the target through improving the domestic content of installation activity has a bigger economic and territorial emission impact than if the target is attained through increasing the domestic content of turbine supply. The composition, as well as the scale, of the domestic content of inputs matters.

We also explored the likely impact of Brexit on our results. Theoretical considerations suggest that the direct impacts of Brexit on the offshore wind sector are ambiguous. Brexit-induced increased trade costs could incentivise location of the supply chain in the UK, an important market for the sector, to avoid higher costs associated with imported inputs from the EU. On the other hand, the increased costs could lead to the supply chain being incentivised to move to the EU if it is regarded as the most important market. In the former case, the result is comparatively good news for the industry (abstracting from the macroeconomic spillover effects resulting from the impact of Brexit on other sectors, which are very likely to be negative). Otherwise, Brexit is likely to adversely affect the economic impact of offshore wind development by reducing domestic content.

Naturally, the further investment in offshore wind capacity involves some additional emissions, but this effect is swamped by the savings in emissions that result from substituting wind for coal in the generation of electricity.[16] Overall, there is a very substantial cumulative saving in emissions across all scenarios - of between 631,800 and 653,400 Mt CO_2e – which accounts for more than a year's

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[16] Note also that, if offshore wind capacity is required to reduce global emissions, the new capacity has to be located somewhere, in which case the emissions associated with construction, installation and operation are unavoidable.

worth of current overall UK carbon emissions. We find that future offshore wind development does indeed generate a “double dividend” in the form of simultaneous and substantial reductions in emissions and improvements in economic activity. It is also the case that, as anticipated, the scale of the economic stimulus arising from offshore wind development is directly and strongly related to the extent of local content. While increases in local content do also increase territorial emissions these are modest relative to overall emissions reductions and decline through time as renewables penetration increases. Overall, our results suggest that current policy emphasis on local content seems entirely appropriate.

Appendices

Appendix A: Breakdown of model aggregation

Model sector	IOC sectors
Coal Mining and quarrying	5
Gas Mining and quarrying	6,7,35
Coke ovens, refined petroleum and nuclear fuel	8,9
Other traded e.g. Food and drink	10-15,18,20
Pulp and Paper	17
Glass and Ceramics	23 Other
Clay, cement, lime and plaster	23.5/6
Iron and Steel; non-ferrous metals	24
Electricity, transmission & distribution	35
Electricity generation - Coal	35
Electricity generation - Gas & Oil	35
Electricity generation - Nuclear	35
Electricity generation - Onshore Wind	35
Electricity generation -Offshore Wind	35
Electricity generation - Pumped	35
Electricity generation - Hydro	35
Electricity generation - Biomass	35
Electricity generation - Other	35
Agriculture; Forestry and fishing	1,2,3
Water	36-39
Construction	41-43
Other Manufacturing and wholesale retail trade	16,20-22,25-33,45-46
Air Transport	50
Other Transport	47-49,51-52
Services	53-94

Appendix B: Offshore wind bridge matrix, in %

Bridge Matrix	Glass and ceramics	Clay	Iron and steel	Generation gas	Generation offshore wind	Construction	Other Manufacturing & trade	Air transport	Other transport	Services
Environmental Survey	0	0	0	2	0	5	0	0	10	83
Seabed survey	0	0	0	2	0	5	0	0	10	83
Met mast	0	0	0	2	0	5	0	0	10	83
Development survey	0	0	0	2	0	5	0	0	10	83
Blades	73	0	0	2	0	10	5	0	5	5
Hub assembly	0	0	73	2	0	10	5	0	5	5
Gearbox	0	0	73	2	0	10	5	0	5	5
Electrical system	0	0	73	2	0	10	5	0	5	5
Other	0	0	73	2	0	10	5	0	5	5
Tower	0	0	78	2	0	10	5	0	5	0
Foundations	0	20	58	2	0	10	0	0	5	5
Array cables	2	0	35	2	0	10	41	2	5	3
Export cables	2	0	40	2	0	10	38	0	5	3
Offshore Substation	0	0	80	2	0	10	3	0	0	5
Onshore electrical	0	0	20	5	0	30	0	0	40	5
IC foundations	0	0	20	20	0	0	5	0	50	5
IC cables	0	0	20	20	0	0	5	0	50	5
IC turbines	0	0	20	20	0	0	5	0	50	5
IC offshore Substation	0	0	20	20	0	0	5	0	50	5
O&M	0	0	0	0	60	10	0	4	0	26

Appendix C: Brexit and the Home Market Effect

Assume that the UK has the largest offshore wind market size in the EU, with exogenous number of units of supply chain inputs of S. In the N other countries of the EU, the exogenous number of supply chain inputs is $S^* < S$. Establishing a supply chain in any location involves (annuitized) investment costs, $F(p) = \frac{1}{fx} p^x$, where $1/p$ is the marginal cost of supplying its home market, τ_1/p is the marginal cost of supplying any other market within theEU, and τ_2/p is the marginal cost of supplying any other market across the EU border, $\tau_2 > \tau_1$. Note that we want to assume that x is sufficiently large that investment costs are approximately linear in market size.

Cost minimisation:

1. Agglomeration in the UK

$$C_{UK} = F(p_{UK}) + \frac{1}{p_{UK}}(S + \tau_{UK} NS^*)$$

where

$$p_{UK} = [f(S + \tau_{UK} NS^*)]^{\frac{1}{x+1}}$$

2. Agglomeration elsewhere

$$C_E = F(p_E) + \frac{1}{p_E}\left(\tau_{UK} S + \left(1 + \tau_E(N-1)\right)S^*\right)$$

where

$$p_E = \left[f\left(\tau_{UK} S + \left(1 + \tau_E(N-1)\right)S^*\right)\right]^{\frac{1}{x+1}}$$

3. Dispersed industry

$$C_D = F(p'_{UK}) + NF(p_D) + \frac{S}{p'_{UK}} + \frac{NS^*}{p_D}$$

where

$$p'_{UK} = [fS]^{\frac{1}{x+1}} \text{ and } p_D = [fS^*]^{\frac{1}{x+1}}$$

Now make some approximations:

- $F(p_{UK}) \approx F(p_E) \approx F(p'_{UK}) + NF(p_D)$
- $p_{UK} \approx p_E$
- $p'_{UK} \approx p_D$

Brexit means that trade costs for trading across the UK-rEU border, τ_{UK}, rise from τ_1 to τ_2, while other trade costs τ_E remain at τ_1. An alternative scenario that we might imagine is the dissolution of the EU, with all trade costs rising to τ_2.

The industry agglomerates in the UK rather than dispersing when $C_{UK} < C_D$ i.e. when

$$(S + \tau_{UK} NS^*)^{\frac{x}{x+1}} < S^{-\frac{1}{x+1}}(S + NS^*)$$

Which clearly becomes less likely as τ_{UK} grows. Rising trade costs make a dispersed industry more likely.

The industry agglomerates in the UK rather than agglomerating elsewhere when $C_{UK} < C_E$ i.e. when

$$S + \tau_{UK} NS^* < \tau_{UK} S + \big(1 + \tau_E (N - 1)\big) S^*$$

This becomes more likely as τ_{UK} grows if $S > NS^*$. The size of this effect is larger the larger is the market size advantage, $S - NS^*$, for the UK.

If both τ_{UK} and τ_E grow (i.e. EU dissolution), then $C_{UK} < C_E$ and agglomerates in the UK rather than agglomerating elsewhere becomes more likely if $S > S^*$. The size of this effect is larger the larger is the market size advantage, $S - S^*$, for the UK.

We see therefore that Brexit can have ambiguous effects on efforts to create a large industrial sector to support offshore wind in the UK. On the one hand, it could support such efforts since all firms want to be located in the UK so as to access the large offshore sector avoiding Brexit related trade frictions. But on the other hand it may either work against such efforts since all firms want to be located in the rest of the EU so as to access its larger offshore sector avoiding Brexit related trade frictions, or it may raise trade frictions to such an extent that firms all want to locate in their local markets, with no country dominating the supply chain. This Home Market Effect can be summarised in the follow table:

	Low Trade Costs	**High Trade Costs**
Low returns to scale	Concentration not important. Proximity not important. Cannot say where industry will locate.	Concentration not important. Proximity is important. Dispersed industry.
High returns to scale	Concentration is important. Proximity not important. Industry locates in a single location, but this is not necessarily the largest market.	Concentration is important. Proximity is important. Industry locates in the largest market.

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