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# A new method to estimate the economic activity supported by offshore wind: A hypothetical extraction study for the United Kingdom

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## Abstract

As well as their role in contributing towards emissions reductions targets, it is increasingly relevant for policymakers to understand the contribution that renewable energy technologies make to the economy. Various methods have been used to quantify impacts, such as job counts, surveys and measures based on economic statistics. Economic modelling approaches on the other hand appear to offer an ability to both provide metrics of interest to policymakers and crucially an understanding of the activities which support that contribution. In this paper, we implement a new method for estimating the activity supported by renewable energy activities; applying a 'hypothetical extraction' of offshore wind—to identify the contribution that such activities make to U.K. economic activity, job quality and national emissions. By undertaking the partial extraction of offshore wind from an aggregated input–output (IO) table and then subsequently from one in which we have separated out the offshore wind electricity sector, we highlight the value of more disaggregation and technology-specific detail in economic accounts. The results from our fullest extraction suggest that in 2010, offshore wind in the United Kingdom supported 10 240 jobs, with 9 in 10 of these jobs either medium or high skill, and contributed £780 million to gross domestic product (GDP). In addition, a significant portion of activity supported by offshore wind is attributable to expansions in capacity rather than operational activities.

KEYWORDS
economic impact, industrial strategy, input–output analysis, low-carbon economy, offshore wind, supply chain

## 1 | INTRODUCTION

Renewable energy activities are crucial in contributing to U.K. climate change targets, such as the recent commitment to reduce greenhouse gas (GHG) emissions to *net*-zero by 2050.[1] A key policy focus is to strengthen activities on the supply of low-carbon electricity. For example, the United Kingdom has set out a renewed direction for offshore wind power—building on its 2017 Industrial Strategy.[2] This strategy also set in motion the process of Sector Deals, through which government and representatives of industry across the economy negotiated a set of objectives and agreements, laying out actions and responsibilities for both to deliver against the government's industrial objectives. Specifically, the Industrial Strategy identifies that 'The move to cleaner economic growth … is one of the greatest industrial opportunities of our time.'[2] This has ushered in a new phase of energy policy where the wider (national) economic benefits are acknowledged as a specific objective of policy.[3]

Offshore wind power deserves particular attention at this time. There have been significant reductions in costs in this technology in recent years. For instance, the prices for offshore wind power through the United Kingdom's Contracts for Difference (CFD) auction reduced from £167/MWh to £44/MWh in current prices. In addition, significant deployment of offshore wind is expected in the coming decades. Vivid economics, for instance, in advice for the Committee on Climate Change, noted that there may be up to 642 GW of offshore wind capacity in scenarios for 2050.[4] The global market is projected to grow by 13% per year to 2040, with—in their 'Stated Policies' scenario—127 GW of offshore wind capacity in the European Union (EU), 107 GW in China and major capacity in the United States (38 GW), Korea (25 GW) and India (16 GW).[5]

Looking at the economic impacts for the United Kingdom, the major economic outcome from the Offshore Wind Sector Deal—in addition to up to 30 GW of capacity and increased exports of U.K. knowledge in offshore wind—is unambiguously stated in terms of spending in the U.K. economy and the creation of jobs.[6] It is clear that more (offshore) wind, rather than less, is implied by the current policy stance so that wind power will be increasingly important for U.K. power production.

Measuring the economic impacts of low-carbon energy policies ex-ante and ex-post must therefore be a top priority. Accurately measuring and defining the contribution of the 'offshore wind' sector, however, is difficult. Common approaches include the use of surveys of businesses, asking if they are involved in a particular activity[7,8] or the identification of specific industries from economic accounts to track developments in economic statistics for a particular group of activities over time. The Scottish Government's characterisation of its 'growth sectors'[9] uses this second approach, for example.[*]

We argue that multisectoral economic accounts and the hypothetical extraction method (HEM) can be useful in identifying the economic contributions of renewable energy activities. To our knowledge, this is the first application of the HEM to the analysis of renewable energy technologies. HEM is a widely used method in industrial analysis[10] and has been applied to consider the economic and environmental impacts of a wide range of individual sectors in a number of countries/regions. In essence, the HE approach developed from 'key sectors' analysis to show the contribution of individual activities and to compare different sectors' economic impacts. Its typical use is to show the effect of full closure of an individual sector, with the loss of its own activities plus the activities which are supported by that sector's sales to and purchases from all sectors in the economy. The sector's impact is measured by the effect of its (hypothetical) extraction from the economy as a whole. Our first novelty is to show how the economic activities associated with the renewable energy sector can be captured within the HE approach, to generate estimates of their contribution to economy and national industrial direct GHG emissions.[†] Our focus is on territorial emissions as these are consistent with U.K. reporting on its progress towards targets.

A second contribution is empirical. We show how the HEM can be used to consider the economy-wide impacts of closure of the offshore wind industry in the United Kingdom. While we use the U.K. offshore wind sector as a case study, the general issues identified, and methods employed have wide applicability to renewables as a whole and to other nations engaged in low-carbon electricity generation. Our application has an additional empirical novelty in that we use an input–output (IO) table with a disaggregated 'electricity sector.' While this is currently treated as a single sector in U.K. IO accounts, disaggregation of the electricity sector is of considerable importance for policy given that a major thrust of energy policy is to alter its composition in favour of renewables. This allows us to compare partial HE of offshore wind from the aggregated electricity sector as it appears in current IO accounts—the best estimate that can be obtained using that database—with HE applied to the electricity-disaggregated IO table. We are therefore able to demonstrate the added value from our disaggregated approach in the illustrative empirical application to offshore wind.

Third, by looking at impacts beyond output—specifically GHG emissions and employment (including the 'skill' classification of jobs)—we move the conversation of economic impact beyond the use of a single metric, namely, jobs,[11] and closer to the concept of 'green jobs.' While the focus on job counts associated with renewable energy is still important for policy, there is growing interest in the 'quality' of employment supported by renewable energy (e.g., the United Kingdom's recent Offshore Wind Sector Deal outlines ambitions to raise the economic contribution to 27 000 *skilled* jobs by 2030[6]). Of course, extension to consider the contribution of renewables to territorial GHG emissions, as well as to the economy, further enhances the policy relevance of the analysis.

The paper proceeds as follows. Section 2 outlines techniques used in the existing literature to explore employment impacts of renewable energy, principally those using surveys,[8] economic statistics[9] and those which use spending approaches and multipliers from IO tables.[12–14] We end this section by setting out the literature gap which this paper addresses. Section 3 summarises our multisectoral modelling approach, including how we apply and refine the HE method to assess the full economic contributions of the offshore wind sector. Section 4 presents the results, while Section 5 concludes.

*See Allan et al.[44] for a review of such counts of employment related to low carbon and renewable energy activity for Scotland.

†In our application, we focus on national industrial greenhouse gas (GHG) emissions, that is, the emissions in the United Kingdom produced by specific economic industries. We thus exclude direct emissions in transport or by households.

## 2 | MEASURING THE OFFSHORE WIND SECTOR: A LITERATURE REVIEW

Measuring the economic contribution of the renewable energy sector is challenging. We illustrate our approach with a specific application to the offshore wind sector to make this question more specific and tractable. There are three approaches to measuring the impact of renewable activities:

- activity by firms identifying themselves as active in renewable energy;
- activity concerned with the production of electricity from renewable technologies;
- activity supported by spending on renewable energy;

Table 1 identifies applications for each of these three methods across a range of countries and renewable energy technologies. The first option—using surveys to identify businesses active in a specific field—is perhaps the metric that users of the estimates of the economic contribution of the offshore wind energy sector expect a count to measure. For instance, in the United Kingdom, the Office for National Statistics (ONS)'s 'Low carbon and renewable energy economy' survey[8]—sent to firms across the economy—asks firms to identify if they undertake activities relating to the use of the good/service they provide across 17 different categories relating to renewable energy or low-carbon activities. For offshore wind, the survey asks firms if they are involved in, 'The production of electricity from offshore wind renewable sources and/or the design, and/or production, and/or installation of infrastructure for this purpose, including operations and maintenance.' Other survey approaches for estimating the number of jobs in green or renewable energy areas have found 3.4 million U.S. jobs in 'Green goods and services' areas in 2011[15] or that there were 104 000 jobs in wind energy in the EU in 2008.[16]

It is instructive to define two commonly used terms: first, the 'direct' effect—that is, those activities which the spending supports in those activities where the spending is made. For example, spending on turbine blades will support activity in the production of turbines. Second, the 'indirect' or 'induced' effects—that is, those activities which are supported elsewhere in the economy by the direct expenditure, through supply chain links (for the former) and additional income and consumption effects for the latter. We show these graphically in Figure 1. In both, the notion of the 'multiplier' is central: The direct expenditure supports further activity through intermediate demand (the supply chain for the activities experiencing the direct effect) and through higher income generating additional consumption. The total economic activity attributable to the renewable energy expenditure is thus identified as the sum of direct, indirect and induced effects.

There is a clear issue here with the identification of renewable activities through such surveys, which is shown in the lower half of Figure 1. Of the activity (e.g., number of firms, turnover or employment) supported by offshore wind, the survey identifies firms which undertake activity for new additions of capacity, operations and maintenance (O&M), plus those companies who 'know' that their products are used in offshore

**TABLE 1** Selected recent studies using surveys, Standard Industrial Classification (SIC) definitions or input–output (IO) analysis to identify the economic contribution of renewable energy activities

| Paper | Geography | Technology | Method |
|---|---|---|---|
| Blanco and Rodrigues[16] | Europe | Wind | Surveys |
| Faulin et al.[30] | Narrave (Spain) | Renewables | Surveys |
| Thronley et al.[31] | UK | Biomass | Surveys |
| Llera et al.[32] | Spain | PV | Surveys |
| Llleral Sastresa et al.[33] | Spain | Wind/PV/thermal solar | Surveys |
| Simas and Pacca.[34] | *Brazil* | *Wind* | *Surveys* |
| Wei et al.[35] | USA | Renewables | Surveys |
| Bishop and Brand[36] | UK | Green energy | SIC |
| Chapple et al.[37] | California (USA) | Green energy | SIC |
| Connolly et al.[11] | Scotland (UK) | Green energy | SIC |
| Yi[38] | USA | Green energy | SIC |
| Yi and Liu[39] | China | Green energy | SIC |
| Allan et al.[40] | UK | Offshore wind | Input–output modelling |
| Connolly[41] | Scotland (UK) | Offshore wind | Input–output modelling |
| Fanning et al.[19] | Wales (UK) | Wave | Input–output modelling |
| Jenniches and Worrell[42] | Aachen (Germany) | PV | Input–output modelling |
| Keček et al.[14] | Croatia | Renewables | Input–output modelling |
| Loomis et al.[43] | Illinois (USA) | PV | Input–output modelling |
| Markaki et al.[20] | Greece | Green energy | Input–output modelling |

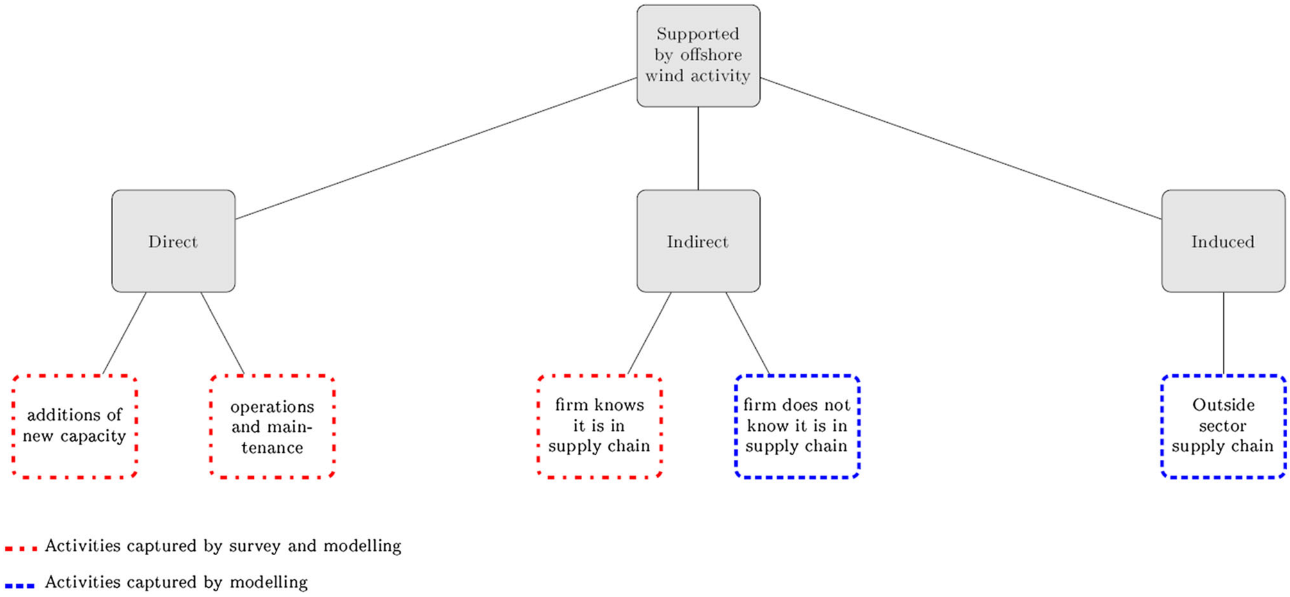


**FIGURE 1** Classification of jobs supported by offshore wind activity

wind (in either O&M or new capacity). Consider the example of a firm producing parts which are used in a gearbox; for instance, the gearbox producer would clearly answer 'yes' to the question above, and if the parts company (supplying the gearbox producer) know that their products are used in that (offshore wind) activity, they would also respond positively. Firms who do not know that their products are used in offshore wind would not respond positively and so would be missing from the reported count. This is identified in Figure 1 as those jobs which would be supported by offshore wind power through 'indirect' links but where the firms do not know that they are in the supply chain.

A final group of survey respondents would be those whose activity is supported by the 'induced' activity of the offshore wind power sector. For instance, those firms receiving spending from workers engaged in direct and indirect activity would likely be unaware that a portion of their activity can be traced back to offshore wind. The examples of retail or accommodation providers illustrate a portion of activity which would be omitted.

The second option would be to identify activities concerned with the production of electricity from offshore wind technologies were such activities identified in economic accounts. The production of electricity has a Standard Industrial Classification (SIC) code[‡] (35.11) and so the IO accounts could identify the purchases and sales for whom this is their predominant activity. The 'direct' activity would be readily identifiable and updated each year (or more frequently) with the release of official statistics.

This approach however has two disadvantages. First, there will be activity in the economy, related directly to offshore wind activity, which does not feature within the SIC related to electricity production. For instance, the construction of new turbines or production of equipment for the addition of capacity would not be considered.[§] Second, the accounts are not sufficiently detailed to identify the production of electricity from different technologies within SIC 35.11 (such as offshore wind).

The third approach examines spending on offshore wind energy (this is crucially important given the commitment to further capacity, not just in the United Kingdom). This expenditure could be captured in the IO tables as the production of goods for investment—a category of final demand, rather than production. Spending-derived estimates of the activity supported by renewable electricity are becoming more common. Jenniches[17] finds that IO modelling of expenditure related to renewable energy is a commonly applied technique. EurObserv'ER[13] sets out an example of this approach through which activity supported by additions to capacity and O&M can be estimated. A spending-driven assessment would identify the activity related to offshore wind spending. Identifying that which is supported by expenditure related to new additions of capacity, this would be the 'direct' activity supported by offshore wind. Additional activity in the firms' supply chain (and these of households) is captured through 'indirect' and 'induced' effects.[¶] There are a wide number of studies applying multipliers to quantify the potential impacts of changes in the scale of renewable energy deployments.[14,18–20] See Jenniches[17] for a recent review of methods and metrics used to quantify the employment impacts of the deployment of renewable energy technologies.

‡Standard Industrial Classification (SIC) is the system of categorising businesses based on their economic activities. In the United Kingdom, SIC2007 provides the current structure of these accounts.[45]

§Siemens Gamesa Renewable Energy, for instance, in the United Kingdom is classified under SIC 42.22—'Construction of utility projects for electricity and telecommunications.'[46]

¶A number of studies use the spending-derived approach and IO multipliers to calculate the economic impact of additions to renewable energy capacity.[12,14,20,29,47–53]

Our approach is perhaps most similar to that explored in Garrett-Peltier,[21] which provides multipliers for different renewable electricity technologies using the IO framework. That paper disaggregates demand and intermediate inputs from within the set of accounts, and the IO method is then used to compare multipliers for renewable energy technologies against those for other investments in energy efficiency or fossil fuel technologies. A research gap remains however as that paper does not seek to embed this measurement of the contribution of renewable energy in the economic accounts for each country. Where our approach uniquely differs from the papers set out in Table 1 is that we embed the purchase and sales links for the renewable energy sector within the set of accounts and can separately identify the economic contribution of the activity related to a specific renewable energy technology. In the next section, we show how our disaggregation of electricity within the multisectoral framework of IO tables and the HEM approach can be used to account for the economic activity supported by renewable energy. Given its increasing future importance to U.K. power generation, we illustrate the usefulness of our HEM approach with a specific application to offshore wind.

## 3 | EXPLORING THE OFFSHORE WIND SECTOR IN A MULTISECTORAL FRAMEWORK

### 3.1 | IO and HEMs

We employ the HEM to calculate the level of output and employment, plus its skill characteristics, which is supported by offshore wind activities in the United Kingdom. A recent application of this method describes this as follows: 'this method uses the interconnectedness between sectors of the economy to quantify the economic importance of individual sectors to supporting activity throughout the economy – in terms of output, and employment.'[22] The required data are given in a set of inter-industry IO economic accounts. These are accounts that are expressed in monetary terms, which detail the nature of consumption and production in an economy for a period of time. In the square analytical IO tables, termed Industry-by-Industry (I x I), each industry in the economy is identified as both a row and a column in the accounts.

We define economic activity in each sector as the sum of intermediate sales to other industries and sales to final demand; we can specify (for a two sector example),

$$X_1 = a_{11}X_1 + a_{12}X_2 + .. + a_{1n}X_n + f_1$$

$$X_2 = a_{21}X_1 + a_{22}X_2 + .. + a_{2n}X_n + f_2$$

where $X_i$ is the output of sector $i$, $a_{ij}$ is a coefficient which represents the output of sector $i$ needed to produce one unit of output of sector $j$, and $f_i$ is the final demand sales of sector $i$. In matrix notation, this can be represented by

$$\boldsymbol{x} = \boldsymbol{Ax} + \boldsymbol{f}$$

which gives the following solution for $X$:

$$\boldsymbol{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{f} \quad \text{or} \quad \boldsymbol{x} = \boldsymbol{Lf}$$

where $I$ is the identity matrix and $L$ is the Leontief inverse matrix.

The extraction of individual industries using HE can be shown using a partitioned matrix where (again with the two sector case)

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{21} \\ a_{12} & a_{22} \end{bmatrix}.$$

In this case, extracting the intermediate connections of sector 1 would mean replacing the elements including sector 1 in the **A** matrix with zero, for example, $a_{11} = a_{21} = a_{12} = 0$. In addition, the final demand for sector 1 would also be set to zero. If $f^*$ and $A^*$ are the matrices after extraction, then the economic contribution to output of sector 1 would be found by the comparison of the pre- and post-extraction economy, that is, $x^* - x = (I - A^*)^{-1}f^* - (I - A)^{-1}f$. Similarly, the impacts on employment, gross value added (GVA) or emissions could be shown with the addition of an appropriate sectoral employment-, GVA- or emissions-output coefficient, respectively.[#]

[#]For instance, with $m_i$ as the employment output coefficient (employment divided by output for sector i), the change in employment associated with the extraction of sector 1 would be $E^* - E = m(I - A^*)^{-1}f^* - m(I - A)^{-1}f$.

While the typical HEM involves the complete removal of an industry identified in the accounts, partial removal, for example, of a firm(s) within an industry is also possible.[10] This is proposed to emulate the consequences of reductions in an industry's capacity to produce. In the case of extraction of a firm from an industry, intermediate sales by the industry should be reduced by the proportion of the industry attributed to the firm ($\alpha$). The row values for industry $k$ (where $k$ = 1, i.e., the industry containing the firm to be extracted)—barring the diagonal elements—are reduced by the portion $\alpha$ so that the matrix $A^{\alpha}$ is given by

$$A^{\alpha} = \begin{bmatrix} a_{11} & \alpha a_{21} \\ a_{12} & a_{22} \end{bmatrix}.$$

In their partial extraction, Dietzenbacher and Lahr[10] note that this is equivalent to assuming that the firm no longer produces the output: equivalent to either lower demand or that the supplies are met by production outside of the economy in question. In the partial extraction, it is proposed that the final demands for sector $k$ can either be kept unchanged or reduced by the value of $\alpha$. The former is equivalent to assuming that previous final demand continues to be met by the parts of the industry not extracted, while the latter assumes that demand falls. In the case of our partial extraction of the offshore wind element of the electricity sector (without disaggregation), we make the assumption that—in keeping with the extraction of industries—both intermediate sales and final demands for the extracted element of the electricity industry are extracted.

In addition, we identify the spending within final demand that is associated with additions of new offshore wind capacity. This means that can we can partition $f$ into renewable (R) and non-renewable (NR) demands for the outputs of each sector:

$$\boldsymbol{f} = \begin{bmatrix} f_1^{NR} & f_1^{R} \\ f_2^{NR} & f_2^{R} \end{bmatrix}$$

This allows us to capture the contribution of both the extraction of the identified sector, plus any additional final demands associated with offshore wind activity, such as new capacity.**

## 3.2 | Data

To implement our analyses—identifying the operational renewable energy sector and new additions to capacity in the economic accounts and then performing the HEM approach—we require data on economic structure and the interconnectedness of sectors within the economy. This is provided by a set of economic accounts, specifically the 2010 IO tables for the United Kingdom as reported in Allan et al.,[23,24] the latest data available at the time of writing. The 2010 IO table is a symmetric I x I IO table with 98 industries (under SICs 2007 definitions), which we aggregate to 39 sectors as given in Appendix A. These data in the IO tables also record socio-economic characteristics by linking two additional indicators to sectoral output so that we can explore the activity supported by offshore wind in more than purely economic (i.e., monetary and output) terms. These are sectoral employment (in Full-Time Equivalent, FTE) and GHG, respectively, so we can construct appropriate employment- and emissions-output coefficients. Base year GHG emissions come from sectoral GHG emissions-output coefficients from fuel use in the United Kingdom.[25] These allow us to focus on industrial emissions from U.K. firms and so relate to changes in the territorial emissions, consistent with the United Kingdom's emissions reporting and emissions reduction targets. Sectoral employment is disaggregated in the IO table by nine occupation categories (Standard Occupational Classification). We aggregate these to three categories that we term ‘High,’ ‘Medium’ and ‘Low’ skilled for presentational purposes.

Two further steps are required, first the disaggregation of the electricity sector in the economic accounts—so that we can identify the economic linkages for the operational offshore wind power sector—and details of the expenditure on new additions to capacity for the Offshore Wind Sector, in order for us to separate these expenditures from whole-economy investment spending in that year. Taking these, in turn, we extend the U.K. IO tables through disaggregation of the electricity sector with details of different (operational) generation technologies. Standard IO tables only report a single electricity sector (SIC 35). As noted earlier, this sector contains firms mapped to the activities within this SIC activity, which include distinct elements—electricity generation (i.e., the production of electricity)—transmission and distribution and retail and trading. These activities are very different, so that the aggregated sector is very unlikely accurately to represent the purchases and sales pattern for any single activity. Second, the nature of generation technologies activities means that there is considerable heterogeneity among the backward linkages of each technology. Third, the forward linkages of each technology are identical—each sells electricity onwards to retail and consumption uses across the economy. The generation mix therefore has 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 in current U.K. IO accounts—comprise a major element of the employment within the sector and so again ideally should be separately identified.

**We do not separately identify exports of offshore wind technology (goods or services); however, this could be added to $f^R$ where data exist.

The data given in Allan et al.[23,24] use information on plant-level production and market price by half-hourly time step based on the framework developed earlier in Connolly.[26] We can thus capture the timing and economic value of production by each generation 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 signals. This disaggregation therefore splits the single electricity sector in the initial tables into 10 sectors: one comprising the non-generation activities (transmission, distribution and supply) and nine separate electricity production sectors: Coal, Gas & Oil, Nuclear, Onshore Wind, Offshore Wind, Pumped, Hydro, Biomass and Other. This approach is of considerable policy interest given the focus on radically changing the composition of the electricity sector in favour of renewables.

To separately identify the expenditure on new additions to capacity, we extend the data from Allan et al.[23,24] to separately identify the portion of investment (i.e., Gross Fixed Capital Formation [GFCF]) spending within Final Demand in 2010, which is consistent with the addition of new offshore wind capacity. This is implemented using the net additions of capacity and the associated spending. We use net additions to offshore wind capacity between 2010 and 2015. Given that the predevelopment phase is roughly 6 years, projects will have spending on their construction for up to 6 years prior to becoming operational. We estimate a vector of investment expenditures in the United Kingdom in 2010 using cost categories within capital expense (CAPEX) costs, their assumed U.K. content and the timing: This totals £1552 million in 2010 prices, with £439 million spent in the United Kingdom. This is equivalent to 0.25% of total investment spending in the United Kingdom in this year.[††] Non-offshore-related GFCF expenditure is necessarily reduced by the scale of this spending associated with offshore wind developments.

## 4 | RESULTS

Having set out the appropriate changes to our economic accounts, we can now undertake the HEM method to explore the economic contribution of offshore wind power in the United Kingdom in 2010. To demonstrate the value of our augmentation of the published economic accounts—with disaggregation of the electricity sector by generation technology and the separation of offshore wind-related Investment spending—we perform the HEM approach under three alternative methods, where each needs additional data beyond the set of IO accounts.

First, we perform the HEM with no disaggregation of the electricity sector by technology. This can be used in cases where there exist economic accounts and where the analysts have information on the share of electricity coming from different sources. We label this approach ‘Method 1: Partial extraction of the offshore wind sector in the aggregated model’ and set out the results from this approach in Section 4.1.

Second, we refine the approach by using information on the operational economic linkages for the specific offshore wind sector. This uses purpose-built disaggregated IO accounts which identify renewable energy by technologies, including offshore wind power. We label this approach ‘Method 2: Extraction of the operational offshore wind sector in the disaggregated model’ and present the results in Section 4.2.

Finally, we build on method 2 by also disaggregating spending related to new additions to capacity in Final Demand. This is our preferred version as it allows for the economic contribution of both operational capacity and new additions to be separately identified. We label this approach ‘Method 3: Extraction of the operational offshore wind sector in the disaggregated model including investment spending’ and show the results in Section 4.3.

### 4.1 | Method 1: Partial extraction of the offshore wind sector in the aggregated model

We begin with the analysis predicated upon the IO table and model in which there is a single aggregated electricity sector. We hypothetically extract the portion of that sector which relates to offshore wind. We estimate that the total output of the U.K. offshore wind sector in 2010 is £104 million, which corresponds to 0.15% of SIC 35, covering Electricity Generation, Transmission, Distribution and Supply. Thus, we use $\alpha = 0.15$ to reduce the $a$ (row) coefficients and final demand for the electricity sector.

Table 2 gives gross output (£m) and the number of FTE jobs supported by the offshore wind sector—when estimated as a 0.15% share of the overall electricity sector. These are identified as ‘direct,’ ‘direct plus indirect’ (Type I) and the ‘direct, indirect plus induced’ (Type II) effects. The ‘direct’ figures are these of the (estimated) offshore wind sector itself. Direct employment is estimated to be 102 FTE jobs, output of £104 million and GVA of £17 million.[‡‡] These direct jobs disaggregated by skill categories show that the majority of jobs are high skill (55%), while 43% and 2% are in medium and low skill categories, respectively.

The offshore wind sector, however, also supports jobs throughout the economy. All products are made using intermediate inputs from other sectors of the economy. The production of intermediates requires the employment of workers. Additionally, sectors sell their outputs to

[††]The nine categories are 1) “Managers & Senior Officials”, 2) “Professional”, 3) “Associate Professional & Technical”, 4) “Administrative & Secretarial”, 5) “Skilled trades”, 6) “Personal service”, 7) “Sales & Customer Service”, 8) “Process, plant & machine operatives” and 9) “Elementary”. 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.[54] Given the increase in offshore wind capacity since 2010, we would expect that this ratio has increased significantly.

[‡‡]Note that since this method uses the aggregate electricity sector, the direct figures for offshore wind are simply the $\alpha$ values multiplied by the values for the overall sector.

**TABLE 2** Direct, indirect and induced effects of the offshore wind sector taking a portion of aggregated electricity sector, U.K. 2010

| | Output (£m) | Gross value added (£m) | Emissions (MKG $CO_2$e) | FTE employment High skill | Medium skill | Low skill | Total |
|---|---|---|---|---|---|---|---|
| Direct | 104 | 17 | - | 56 (55%) | 44 (43%) | 3 (2%) | 102 |
| Direct, plus indirect (Type I) | 166 | 47 | 246 | 184 (47%) | 181 (46%) | 28 (7%) | 394 |
| Direct, indirect, plus induced (Type II) | 306 | 100 | 365 | 527 (45%) | 521 (44%) | 125 (11%) | 1173 |

households and will therefore be impacted by changes in household incomes (through wages). The scale of these two effects is captured in the 'indirect' and 'induced' effects, respectively (see, e.g., Allan and Ross[22]) for a more detailed discussion).

Turning to the indirect and induced impacts of the (estimated) offshore sector, the ratios between direct and indirect and induced effects are, of course, constrained to be identical to those for the aggregate electricity sector in this method.

The 'Direct, plus indirect' (Type I) effect for output is 1.6 times the direct effect (£166 m/£104 m)—and that of employment is 3.9 times larger (394/102). GVA is less than the level of output as not all the spending falls on goods produced in the United Kingdom (recall, we have adjusted for local content) and only a portion of spending falls on GVA in each sector.

The Type II effects ('Direct, plus indirect, plus induced') show that these ratios increase to 2.9 and 11.5 for output and employment, respectively. Emissions associated with the offshore sector total 246 MKG $CO_2$e emissions in the Type I case and 365 MKG $CO_2$e under Type II. While these economic and emissions results are interesting in themselves, we are particularly interested in how the results of this 'naïve' extraction of offshore wind compare to those obtained where we use the IO with disaggregation of the offshore electricity generation. Note that these emissions, of course, reflect the GHG emissions intensity of the electricity sector as a whole: Unthinking use of aggregate sectoral data can lead to particularly misleading results (as we confirm in Section 4.2).

The Type II employment and output impacts across sectors of the economy are summarised in Figure 2 as a 'running total' (i.e., summing up the shares of total supported employment/output by sector in turn). Figure 2 shows that half of the total output supported by offshore wind on this approach is located directly in Sector 16, Electricity, transmission & distribution (ELE), while only 13% of total employment is supported within that sector. The (partially extracted) ELE sector supports employment mainly in Sectors 30 and 36, Wholesale & Retail Trade (WHO) and Services (SER), with 16% and 23% of total employment respectively. Output is mainly supported in the SER sector (Sector 36), with 13% of total output, and Sector 3, Crude Petroleum + Natural Gas & Metal Ores + Coal (CRU), supporting 8% of total output. We expect these sectoral linkages to differ when using the offshore wind-specific disaggregation in the following section.

## 4.2 | Method 2: Extraction of the operational offshore wind sector in the disaggregated model

Table 3 reports output and employment supported by the offshore wind sector, now reflecting the actual cost structure of the operational offshore wind sector as identified in the disaggregated set of IO accounts given by Allan et al.[23,24]

The direct employment supported by offshore wind is 134 jobs and £104 m in output. These 134 jobs are further broken down by three skill categories, showing that the majority (59%) of the jobs are within the high skill category, 38% are medium skilled, and only a very small share of jobs (3%) are in the low skill category. This would indicate that the operational sector itself is relatively high skilled—both compared to the U.K. economy as a whole and the aggregate electricity sector.[§§] Note that the direct effects (other than output, of course) are higher than the levels implied by applying HEM to the table with the aggregated electricity sector and in the case of GVA much higher.

Type I effects show that output is 1.7 times greater than the direct effect (£182 m/£104 m)—and that of employment is 6.2 times (842/134). This suggests that the majority of jobs that the offshore wind sector supports are outwith the sector itself. The Type I supported skilled jobs are a 4.6 multiple of these in the offshore wind sector itself (362/79), for medium skilled, and for low skilled the ratios are 7.9 (402/51) and 19.8 (79/4), respectively. Although overall there is a large high skill component, there is a shift towards medium skilled labour as impacts beyond the offshore wind sector itself are considered. Now 43% of total jobs are highly skilled, 48% are medium skilled, and 9% are low skilled.

The Type II results highlight similar key findings. That is, while output is 2.5 times greater (£262 m/£104 m), jobs supported throughout the economy are a multiple of 11.5 times of these directly in the sector (1546/134). Along with the increased number of jobs supported as compared to the Type I effects, there is a shift towards low skilled jobs (bringing the skill distribution closer to the U.K. average). The Type II jobs are 43%

[§§]The data from the U.K. IO table indicate that 42% of workers are high skilled, 44% medium skilled and 14% low skilled, respectively.

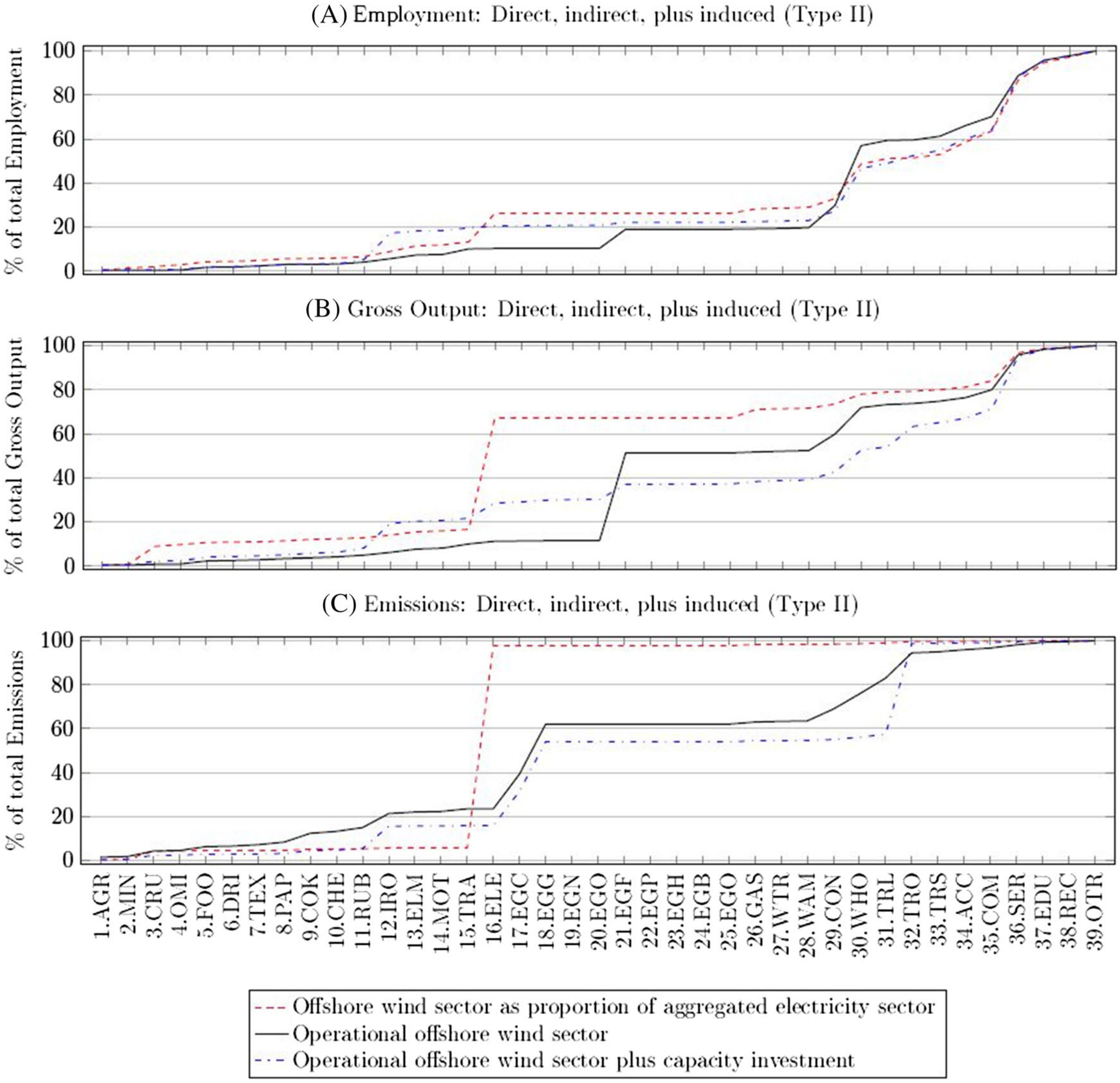


**FIGURE 2** Direct, indirect and induced employment, gross output and emissions by individual sector as proportion of total

**TABLE 3** Direct, indirect and induced effects of the operational offshore wind sector, U.K. 2010

| | | | | FTE employment | | | |
|---|---|---|---|---|---|---|---|
| | Output (£m) | Gross value added (£m) | Emissions (MKG $CO_2$e) | High skill | Medium skill | Low skill | Total |
| Direct | 104 | 179 | - | 79 (59%) | 51 (38%) | 4 (3%) | 134 |
| Direct, plus indirect (Type I) | 182 | 215 | 8 | 362 (43%) | 402 (48%) | 79 (9%) | 842 |
| Direct, indirect, plus induced (Type II) | 262 | 253 | 23 | 665 (43%) | 704 (46%) | 176 (11%) | 1546 |

high skilled, 46% medium skilled and 11% low skilled. The Type II skilled jobs are an 8.4 multiple of these in the offshore wind sector itself (665/79); for medium skilled and low skilled, this is 13.8 (704/51) and 44.0 (176/4), respectively.

These results establish that there are significantly more jobs supported throughout the economy by the offshore wind sector than was implied by the analysis in Section 4.1. Disaggregation of the offshore wind sector reveals an estimate of employment that is almost 1.5 times larger than that derived from the simple partial extraction of the electricity sector (1546/1173).

Typically, the offshore wind sector is regarded as a *high skill sector*—a feature also reflected in our results of the direct effects. However, when considering the system-wide results, it is apparent that the offshore wind sector supports a wider distribution of skills. Particularly, there is a shift away from high skill jobs to medium and to low skilled jobs when considering the skill component of jobs supporting activities within the offshore wind sector.

While the offshore wind sector does not generate GHG emissions itself, it does have an impact on emissions in a system-wide context. As such, when taking into consideration the 'direct, indirect, plus induced effects,' 23 MKG $CO_2$e emissions (less than 1% of total U.K. emissions) can be attributed to the offshore wind sector.[¶¶] Note that this is less than 10% of the emissions attributed to offshore wind by Method 1, strongly reinforcing the importance of conducting the analysis with an appropriately disaggregated electricity sector.

Figure 2 shows that 40% of the total output contribution is directly in the operational offshore wind sector. As previously, this sector has strong linkages to the Wholesale and Services sectors, Sectors 30 and 36, carrying 12% and 16% of total output, respectively. In contrast to the previous case (Section 4.1), however, the offshore wind sector (Sector 21, EGF) does not have strong linkages to Sector 3 (Crude Petroleum), for example, showing a very different distribution of impacts across sectors when only the aggregate Electricity sector is considered. Similar observations can be made for employment. The main linkages of the offshore wind sector are here to Sectors 29, 30 and 36, Construction (CON), Wholesale and Services, accounting for 10%, 27% and 18% of total employment, respectively.

## 4.3 | Method 3: Extraction of the operational offshore wind sector in the disaggregated model including investment spending

Table 4 shows output and employment supported by the offshore wind sector, including both the operational (disaggregated) offshore wind sector and the element of GFCF expenditure associated with additions of capacity. As we are extracting elements related to final demand plus that removed in Section 4.2, we expect to see larger numbers across all categories of impact. It is therefore not surprising that here we see the largest economic contributions. The scale of the differences is perhaps surprising at first glance, but they reflect the scale of the sector's expansion and the distinctive linkages of CAPEX as against O&M expenditures.

The 'direct' figures are those of the operational wind energy sector itself, plus those activities directly involved in meeting investment demand. Direct employment is estimated to be 2453 jobs, with £542 million of output and £327 million of GVA. By skills types, the direct jobs are disaggregated as follows: 1046 high skill (43% of total direct employment), 1209 medium skill (49%) and 198 low skill (8%). It is interesting to note that, compared to Tables 2 and 3, this is the first instance of direct employment being concentrated in the medium skill category and that the low skill share of direct employment has more than doubled (from 3% to 8%) as a consequence of incorporating the impacts of investment expenditures on offshore wind capacity.

From Table 4, we see that the Type I effects show that supported output is 1.8 times and GVA is 1.6 times greater than the direct effect. Employment supported by Type I is 5319 jobs, some 2.1 times greater than direct jobs. This is a much-reduced ratio compared to Section 4.2 (where total employment was 11.5 times larger than direct employment) and is explained by the larger direct figure for offshore wind activity when employment associated with investment spending is included. Type II employment is 10 243, 4.2 times greater than the direct employment. We note that this figure of 10 243 is around 0.04% of total employment in the United Kingdom in 2010.

Looking at the distribution of employment skills categories for Type I and Type II employment, these show that the (rounded) shares of employment are identical for Tables 2 and 3, despite the difference in scale. Including investment expenditures therefore appears to increase the scale of economic activity considerably—output, GVA and employment increase by 5.8 times, 3.1 times and 6.6 times, respectively, between Tables 2 and 3—but the distribution of employment across high, medium and low skill activities remains the same. This is an important insight which we would not expect to be general finding—but will reflect the level of aggregation, the distribution of investment expenditure across U.K. economic sectors and the detail of skills disaggregation within the table.

**TABLE 4** Direct, indirect and induced effects of the operational offshore wind sector *plus capacity expenditures*, U.K. 2010

| | Output (£m) | Gross value added (£m) | Emissions (MKG $CO_2$e) | FTE employment: High skill | Medium skill | Low skill | Total |
|---|---|---|---|---|---|---|---|
| Direct | 542 | 327 | 331 | 1046 (43%) | 1209 (49%) | 198 (8%) | 2453 |
| Direct, plus indirect (Type I) | 952 | 509 | 633 | 2280 (43%) | 2565 (48%) | 474 (9%) | 5319 |
| Direct, indirect, plus induced (Type II) | 1,507 | 780 | 734 | 4405 (43%) | 4683 (46%) | 1155 (11%) | 10 243 |

[¶¶]The details of the construction of the base year emissions data are given in Allan et al.[25]

In contrast to Sections 4.1 and 4.2, Figure 2 shows a more nuanced distribution across sectors in terms of output and employment. A large proportion of output is now in Services (24%), Wholesale (10%) and Iron, steel + metal (IRO) sector (11%), while the (operational) offshore wind sector contributes 7% to total output. Employment impacts are ranked similarly. Almost one-quarter (24%) of total employment is carried by the Services sector, 19% by the Wholesale sector and 12% by the Iron sector, with only around 1% of total employment contributed by the offshore wind sector itself. We note that there are significantly greater emissions associated with the offshore wind sectors' activities in this scenario. Comparing the emissions column between Table 3 and 4, we see that there are very substantial additional emissions supported outside of the operational offshore wind sector, related to the whole economy multiplier effects of spending on new capacity in the United Kingdom.

We end on a note of caution. The dominance of investment expenditure effects in this analysis reflects the significant expansion of offshore wind capacity in the relevant period. In a static steady state, investment expenditures would be expected to decline significantly, so as ultimately to equal the level of replacement investment required to maintain the capacity of the sector. In such circumstances, the relative scale of investment expenditures would be much reduced, and the economic and emissions impacts would reflect this new composition of spending. However, for the foreseeable future, significant increases in offshore wind capacity continue to be anticipated, for example, in the recent Offshore Wind Sector Deal[4], so that the impacts identified here are likely to maintain their policy relevance for some time.

## 5 | DISCUSSION AND CONCLUSIONS

Measuring the economic impact of renewable energy technologies is important to help policymakers understand the consequences of their decisions. While a number of methods have been used—including surveys, economic accounts and simple IO modelling and analysis of renewable energy expenditures—these measures have not been embedded in a set of economic accounts from which additional analysis can be undertaken. We have illustrated an approach that uses the widely applied HEM and augments the existing accounts with sector-specific information on renewable energy generation and additions to capacity. We apply this in the case of the offshore wind to illustrate how that sector's activities can be separately considered in IO accounts and identified the levels of activity—output, GVA, employment (disaggregated by skills) and national industrial direct GHG emissions—supported by the offshore wind sector in the United Kingdom.

We show (in Section 4.1) that a 'naïve' extraction of offshore wind using an IO table and model which, in accordance with current official accounts practice, treats the electricity sector as a single, aggregated sector, understates (compared to Section 4.2) the scale of economic activity (i.e., GVA) that is attributable to the sector (as measured using an appropriately disaggregated IO accounts and model). This confirms the tangible benefits from systematic disaggregation of IO tables to reflect subsectors of interest, rather than relying on ad hoc techniques for partial extraction, particularly in the case where the aggregate sector contains very heterogeneous activities. Naïve HE from a standard, aggregated IO table also proves very misleading in terms of the scale of emissions attributed to the offshore wind industry. The effective monitoring of the economic and emissions impacts of offshore wind, and other renewables sectors, requires an appropriately disaggregated IO table and model. Method 3 is thus our preferred method as it both uses the most detailed economic information on the renewable energy technology and captures not only operational activities but also those related to capacity additions. Our results from our preferred HEM indicate that operational offshore wind activity and the spending associated with additions to capacity supported 10 243 jobs in the United Kingdom in 2010, with these jobs broadly shared between high and medium skill activities. Given our approach uses (estimated) expenditures, we can say that all of the jobs identified in this way are supported by the offshore wind sector, either directly, indirectly or induced. Our approach thus differs from surveys where firms need to note what proportion of their staff are active within predefined and specific wind energy activities, as described in the survey question. Focusing only on the operational offshore wind sector itself—that is, activities involved in the production of electricity from offshore technologies—would have underestimated this impact by almost 8500 jobs. In addition, focusing on 'direct' jobs in generation activities, which our analysis suggests are predominantly high-skilled, would have missed the important contribution to medium and low skill jobs, which are supported by the sector in the rest of the economy. We note that the ONS survey estimates that in 2017, 7200 jobs in the United Kingdom were in offshore wind. However, this number cannot be broken down into direct and indirect, or attributed to operation and maintenance, rather than the construction of new projects. Nor is there any comment on the skills of the workers in those roles.

While our focus is methodological, our approach also has relevance for policymakers. To support decision-making for renewable energy, policymakers need information not only on the total number of jobs that technologies support but also on what drives the overall number, so as to enable better decision making. Without this, policy decisions around the promotion of renewable energy in part for their economic impacts risk being based on confusing, misleading or, indeed, false evidence. In addition, economic impacts during the lifetime of renewable energy technologies will be driven in part by differences in local content. Our approach would permit sensitivity analysis—which is not conducted here—over how the measured contribution would change under alternative assumptions about, for instance, local content or alternative (local) supply chains for renewable energy. Furthermore, our findings make clear that much of the economic contribution of renewable energy is felt outside of the electricity sector itself, and across the economy, establishing the necessity of a system-wide evaluation of the economic consequences of renewable energy policies.

Several further points can be made. First, our analysis uses the most recent IO table for the United Kingdom, which dates from 2010. There have clearly been significant changes in the scale of offshore wind generation and its share of the electricity mix since then. These (significant) increases in investment in the offshore wind sector mean that we would now expect the scale of the direct activity supported by the sector to have increased. Additionally, plans to continue to develop future offshore wind capacity suggest that there will be considerable further investment activity related to offshore wind. Our methodological framework could straightforwardly be applied to more recent IO tables for the United Kingdom as they become available or to regions/nations where more recent tables have been published.[##] Further research on the extent of domestic supply chains and local content in the construction phase could help to validate the outputs from the HE approach employed here.

Second, our estimates of local content associated with investment spending may be incorrect. We have used estimates of the extent to which expenditure on capacity by category of costs will be sourced in the United Kingdom and use an overall U.K. content share of 28%. This is lower than more recent estimates of U.K. local content,[27] which suggest that in 2017, this had increased to 48%, up from 43% in 2015. This appears to have been increasing in recent years with the development of the U.K. supply chain for offshore wind construction projects. The Whitmarsh 'Supply Chain Review' argued for a better understanding of the U.K. content—including 'analysis of its upstream origin'—and that developers should work towards demonstrating that '10% of the total capital cost should incorporate intellectual property developed and owned by UK companies.'[28] Recent work by Allan et al. demonstrates the importance of local content in CAPEX for the economic impacts from the development phase for offshore wind in the United Kingdom.

Third, we have not undertaken any analysis of impacts across the regions of the United Kingdom. In addition to the overall economic contribution of offshore wind, the recent Sector Deal acknowledged that there has already been—and may continue to be—a geographic clustering of U.K. offshore wind activity. It is noted in the Sector Deal, for instance, that such clusters 'are already emerging, generally located close to windfarms or areas with a strong, pre-existing manufacturing base, oil and gas, or R&D presence.'[6] Accordingly, there may be compelling reasons to consider the geographical distribution of the sector's contribution through extending the HE to a multi-regional framework.

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## PEER REVIEW

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[##]Input–output accounts for many countries are now provided for academic purposes, including the World Input–utput Database (http://www.wiod.org/home) and the OECD's Inter-Country Input–Output Tables (http://www.oecd.org/sti/ind/inter-country-input-output-tables.htm)

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## APPENDIX A: SECTORS, CODES AND ABBREVIATIONS

| **1. AGR** | **Agriculture, forestry & fishing** |
|---|---|
| 2. MIN | Mining & quarrying |
| 3. CRU | Crude petroleum + natural gas & metal ores + coal |
| 4. OMI | Other mining & mining services |
| 5. FOO | Food (+tobacco) |
| 6. DRI | Drink |
| 7. TEX | Textile, leather & wood |
| 8. PAP | Paper & printing |
| 9. COK | Coke & refined petroleum products |
| 10. CHE | Chemicals & pharmaceuticals |
| 11. RUB | Rubber, cement, +glass |
| 12. IRO | Iron, steel + metal |
| 13. ELM | Electrical manufacturing |
| 14. MOT | Manufacture of motor vehicles, trailers & semi-trailers |
| 15. TRA | Transport equipment + other manufacturing (incl repair) |
| 16. ELE | Electricity, transmission & distribution |
| 17. EGC | Electricity generation—coal |
| 18. EGG | Electricity generation—gas & oil |
| 19. EGN | Electricity generation—nuclear |
| 20. EGO | Electricity generation—onshore wind |
| 21. EGF | Electricity generation—offshore wind |
| 22. EGP | Electricity generation—pumped |
| 23. EGH | Electricity generation—hydro |
| 24. EGB | Electricity generation—biomass |
| 25. EGO | Electricity generation—other |
| 26. GAS | Gas; distribution of gaseous fuels through mains; steam & air conditioning supply |
| 27. WTR | Natural water treatment & supply services; sewerage services |
| 28. WAM | Water management & remediation |
| 29. CON | Construction—buildings |
| 30. WHO | Wholesale & retail trade |
| 31. TRL | Land transport |
| 32. TRO | Other transport |
| 33. TRS | Transport support |
| 34. ACC | Accommodation & food service activities |
| 35. COM | Communication |
| 36. SER | Services |
| 37. EDU | Education health & defence |
| 38. REC | Recreational |
| 39. OTR | Other private services |