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The co-benefits of offshore wind under the UK Renewable Obligation scheme: Integrating sustainability in energy policy evaluation

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ABSTRACT

Offshore wind energy is a key technology for decarbonising the UK electricity system. It also delivers significant socio-environmental co-benefits. Assessing these co-benefits is essential for energy policy under turbulent energy market conditions emerging in the wake of geopolitical unrest. This study focuses on assessing the co-benefits and costs associated with offshore wind electricity generation for the Renewable Obligation scheme in the UK, which although being phased out, currently supports more offshore wind generation in 2023 than its Contracts-for-Difference replacement scheme. Comparing offshore wind co-benefits with support scheme costs provides an objective evaluation of the scheme's success. Results indicate that reduced energy imports contribute to co-benefits of £5.9 ± 0.3bn and £4.9 ± 0.3bn in simple and flexible scenarios respectively. Emissions reductions lead to £4.4 ± 0.9bn in simple and £3.9 ± 0.8bn in flexible scenario. The employment benefits amounted £1 ± 0.2bn. The cost of the Renewable Obligation scheme amounted to £18.8 ± 3.8bn, indicating that the co-benefits can cover 60% and 52% of the policy costs, in simple and flexible scenarios, respectively. This analysis supports a case for monetising the wider co-benefits of energy technology implementation to support institutions and policy makers in the integration and evaluation of sustainability in energy policy in a way that goes beyond the electricity price.

1. Introduction

Offshore wind energy plays a key role in electricity sector decarbonisation to meet net zero greenhouse gas emissions targets (ONS, 2022). The UK has installed 14.7 GW of offshore wind capacity by the end of 2023, accounting for 26% of total installed capacity and 17.4% of total electricity generation (DESNZ, 2023a). Consequently, the UK hosts the second largest offshore capacity after China, with ambitious Government targets to increase capacity almost fourfold to 50 GW by 2030 (BEIS, 2022). The UK carbon budget for the electricity sector envisages deployment of 95 GW in the 'balanced pathway' scenario by 2050 (CCC, 2020). However, in practice, predicted installed capacity might fall short of this target: The International Energy Agency (IEA) predicts capacity increases to at least 27 GW by (IEA, 2023).

Technological progress and financial learning have contributed to accelerated offshore wind development thus far – primarily by increasing turbine size, substantially reducing the cost of electricity (Shields et al., 2021), and lowering the cost of capital (Beiter et al., 2024). Consequently, offshore wind generation costs fell significantly from £120/MWh in 2017 to below £50/MWh in 2023 (Jansen et al., 2020). Thus offshore wind energy remains a viable decarbonisation technology despite financing and supply change challenges experienced since 2023 (Jansen, 2023).

Despite substantial market uptake, offshore wind experiences a range of economic, social and political barriers to deployment. These challenges can be broadly categorised as: market failures and distortions, investment challenges against rising industry costs, lack of political support from central and regional governments and planning authorities, technical, geographic (location) and environmental impact challenges, and issues concerning social opposition and acceptance of wind technologies (Cotton, 2019; Diógenes et al., 2020; Sadorsky, 2021). Yet despite myriad industry and policy challenges, the UK is a key case study for the successful economic and policy framework for renewable energy investment.

The UK Government has implemented financial support to offshore wind energy through two different policy schemes. First, is the

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Renewable Obligations (RO) scheme. The RO scheme was introduced in 2002 across England, Wales, and Scotland, and in 2005 in Northern Ireland, to support renewable electricity deployment (including offshore wind generation) across the UK. The scheme supported 22 TWh of offshore wind energy, 28 TWh of onshore wind energy, and 31 TWh of other renewable generation in the UK financial year 2022/2023. The policy is a quota system and requires suppliers to present a specific number of Renewable Obligation Certificates (ROCs) per MWh of electricity supplied to the regulator Ofgem. The ROC payment support can be classified as feed-in premium policy instrument (Jansen et al., 2022; Kitzing, 2014). Electricity suppliers can either meet their obligation by making payments into the buy-out fund, or else by acquiring ROCs from generators (Ofgem, 2023). In total, Ofgem issued 105 million ROCs in 2021–22.

Onshore and offshore wind energy has the highest share of electricity generation, accounting for 29% and 27% of all electricity generation respectively, through the RO scheme (see Fig. 1) (Ofgem, 2023). ROCs are tradeable, however, their buyout price of £59/MWh in 2023/2024 is the guideline price paid to generators (see also Fig. 3), in addition to any revenue from selling electricity on the wholesale electricity market. ROC buyout prices are adjusted for inflation using the Consumers Prices Index (CPI). Market prices can fluctuate based on the ROCs required by energy suppliers – thus demand and supply may change prices. Offshore Wind receives 2 ROCs for every unit of electricity generated. This means that offshore wind farms receive at least £118/MWh under the RO scheme, plus any wholesale electricity market revenues. The RO scheme was closed to new generators on April 1st of 2017, following the Electricity Market Reform (EMR) policy process. However it continues supporting existing generators up to 2037 (DECC, 2014), and therefore remains a key energy policy mechanism.

Second, the Electricity Market Reform (EMR) has introduced the Contracts-for-Difference (CfD) support scheme, superseding (and ultimately retiring) the RO scheme. Following success in the UK, CfDs are becoming the global standard in supporting new offshore wind capacity, as policy makers shift away from legacy schemes towards CfDs (Jansen et al., 2022). CfDs provide a financial settlement for electricity for 15 years in total between the market reference price and the strike price, indexed to $£_{2012}$. The strike price is typically determined at an auction where the bidder of the lowest strike price is awarded a CfD.[1] Under the CfD scheme, 20 GW of CfD contracts for offshore wind are recorded, of which 4.8 GW is fully operational (18 TWh) as of mid-2023, reaching 8.8 GW in 2024 (37 TWh), with an additional 4 GW either under construction or under commission (DESNZ, 2023b). The first CfD auction was held in 2015, with technology-specific pots for offshore wind (and others), with the first wind farms coming online in 2017. All future UK offshore wind farms will have to tender for CfDs – or go fully merchant – following seabed lease auctions by the Crown Estate. Past CfD auction have seen the strike prices plummet from $£_{2012}$120/MWh for plants operational by 2017, to below $£_{2012}$40/MWh for power plants commencing operation on 2023/2024 (DESNZ, 2023b; Jansen et al., 2022, 2020). The most recent auction in September 2023 led to no energy companies submitting bids, and earlier in 2023 one developer halted progress on a previously contracted project (Jansen, 2023). Reportedly, auction failure followed warnings from developers that the government-set maximum strike price of $£_{2012}$44/MWh was too low to account for cost pressure originating from construction supply chains and financing cost issues. It is estimated that 5 GW of offshore projects remain at risk (either cancelled or delayed), further jeopardising the national 50 GW 2030 target (Ambrose, 2023).

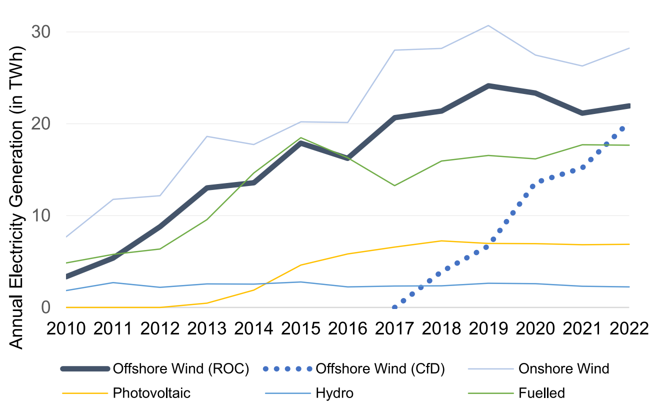

Fig. 1. Electricity generation by technology based on Renewable Obligation Certificates and for offshore wind in the UK (DESNZ, 2023b; Ofgem, 2023).

Despite the introduction of the CfD scheme, the RO scheme still supports most offshore wind developments in the UK, up until 2023. It thus remains a relevant offshore wind policy mechanism. Analysing and understanding the RO scheme is warranted by its widespread adoption, and similar energy policy schemes across the world that rely upon renewables quota systems. For example, similar quota systems exist in Italy, Australia and Texas (Blyth et al., 2023; IRENA, 2013), making assessment of the UK's RO scheme relevant to other policy contexts globally. Recent challenges for the UK auction scheme to attract bidders requires energy economics research and policy practitioners to assess the broader socio-economic and environmental benefits of offshore wind. For this, looking beyond the electricity price may further facilitate uptake, market deployment and political support for the technology.

The RO scheme has stimulated renewable energy generation including offshore wind in the UK which lead to higher energy supply diversification and more resilient energy system (Bean et al., 2017; Di Cosmo and Valeri, 2018; Gil et al., 2012). Consequently, adding offshore wind energy results lower energy prices. However, it has not been sufficient to offset the costs associated with the RO scheme in the UK (Shao et al., 2022). An offshore wind energy-driven transition also provides broader sustainability co-benefits. These include electricity system, economic, and environmental benefits that go beyond immediate carbon savings compared to fossil fuel alternatives (Glasson et al., 2022; Kaldellis et al., 2016; Rose et al., 2022; Salvador and Ribeiro, 2023). In this study, we take sustainability co-benefits as assistances for goods and services that extend beyond any direct benefit, presenting a non-monetised surplus for societies (i.e. positive externalities) (Fujiwara and Campbell, 2011). Furthermore, sustainability co-benefits also refer to actions that remove social costs including environmental damage and pollution (i.e. negative externalities) (Rutz and Janssen, 2014). Market failure occurs due to the lack of market capacity to capture the impact of sustainability co-benefits, and under these circumstances government intervention in energy markets becomes necessary (Green and Vasilakos, 2011). Sustainability co-benefit assessment is therefore valuable in identifying the effects of economics on social systems and communities, and can thus be used in energy policy, planning, and decision making, to ensure that the needs of diverse social groups are considered (Glasson et al., 2022; Madlener and Myles, 2000).

The primary advantage of offshore wind energy deployment is of course the climate change mitigation benefit from CO_2 emission reduction (Glasson et al., 2022; Salvador and Ribeiro, 2023). However, there are also benefits across the so-called 'energy trilemma': including reducing the need for fossil-fuel based energy imports leading to improvements in national energy security (Ortega-Izquierdo and Del Río, 2016; Ortega et al., 2013a; Sovacool, 2013), and potentially improving long term energy affordability by alleviating price shocks within volatile fossil fuel markets (Adom et al., 2021; Zhao et al., 2022).

Job creation in the supply chain of offshore wind energy is the second important sustainability benefit associated with offshore wind

[1] Note that the CfD for Hinkley Point C Nuclear Power Plant was negotiated between the government and the generator without an auction.

energy (Allan and Ross, 2019; Dinh and McKeogh, 2019; Rose et al., 2022) – one that is essential to acheiving a *just transition* for workers living in fossil fuel-intensive employment regions (Swilling, 2020). The offshore wind energy industry offers the highest number of jobs within the UK renewables sector – potentially employing over 97,000 people by 2030, including about 61,000 and 36,000 direct and indirect jobs, respectively (IRENA, 2022). It is important as a research and policy priority to understand the broader sustainability benefits of offshore wind, and to compare them with relevant policy costs in order to support decision-making to utilise, if not maximise, such benefits (Bean et al., 2017; Pashakolaie et al., 2023). The objective of this paper is therefore to identify and assess the co-benefits of offshore wind energy, to evaluate the effectiveness of the RO scheme as a dominant support policy in the UK with reference to its application to other quota policy frameworks worldwide, and to the furthering of UN Sustainable Development Goals (SDGs) including greenhouse gas emission reduction (SDG13), the impact on energy security (SDG7) from the provision of renewable energy, and employment (SDG8) through electricity generation impact on direct and indirect jobs.

The following section details the materials and methods used. We develop the assessment for evaluating ROC costs and measuring the co-benefits from emissions reductions, employment and avoided imports in section two. This is followed by results and discussion in section three and four respectively. We draw our conclusions thereafter.

2. Material and methods

Policy evaluation involves assessing the costs and benefits of implementation of alternative policy options, focusing upon both positive and negative impacts. Positive impacts, also known as co-benefits, contribute to the wider social and economic value of economic policy choices, a concept originated from welfare economics, emphasising the significance of social and public value that extends beyond the sole market value. Social value encompasses the improvements in the socio-economic dimensions of economic decision-making, including: welfare, wellbeing within society, environmental improvements, reduced crime and increased security, and expanded employment, each of which are often not efficiently measured by market mechanisms (Treasury, 2022).

This study presents a policy decision-making framework to incorporate social value into offshore wind energy policy. This framework comprises methods for evaluation and appraising of energy policy, divided into two mains components: policy supporting cost associated with ROCs, and co-benefit (Fig. 2.) The co-benefits of ROCs offshore wind policy encompass various aspects including emission reduction, energy import reduction, and job creation benefit. Various economic methods are employed to assess and quantify these co-benefits in the monetary value (section 2.1.,2.2.,2.3. and 2.4.). To assess climate benefit, the United Nations Framework Convention on Climate Change (UNFCCC) framework including energy technoeconomic parameters are applied to measure all possible offshore wind substitution scenarios in the UK energy mix and to finally quantify carbon reduction achieved through the implementation of offshore wind energy projects. The UNFCC framework has been extended to capture the energy security and energy import reduction value. Labour economics concepts are used to calculate the employment related benefits; taking into account factors such as number of new jobs introduced by offshore wind energy, the number of job losses due to avoiding fossil fuel power plant establishment, wage levels within the offshore wind sector, and the unemployment rate. Finally, offshore wind energy policy support through ROCs scheme is evaluated by assessing the extent to which the costs of ROCs are covers by the value of the co-benefits. Finally, sensitivity analysis has been applied to explore how changes in basic assumptions affect the results of co-benefits/ROCs cost ratio in both scenarios. To provide a wide sensitivity range, 5%,10%,15%, and 20% variation in key assumptions has been implemented in this study.

To account for all sources of model variation, one key assumption from each component was included in the model. In total, the analysis covered sensitivity to four key assumptions: (1) the cost of ROCs, (2) the shadow price of carbon as a crucial assumption in emission benefit, (3) the LCOE of offshore wind as an uncertain assumption of import reduction benefit, and (4) employee salary as a key assumption in employment benefit.

2.1. ROCs support cost

Under the RO scheme, the UK energy market regulator Ofgem allocates ROCs to accredited renewable generators. These ROCs can be sold by the generators to suppliers in the market. Alongside the revenue earned from selling electricity in the wholesale market, these ROCs provide an additional source of income for renewable generator companies. Energy suppliers must submit a certain number of ROCs to the energy regulator. If they fail to do so, they must pay a penalty based on the buy-out price (Li et al., 2020). To cover these costs, energy suppliers commonly pass on the ROC expense to consumers through energy bills.

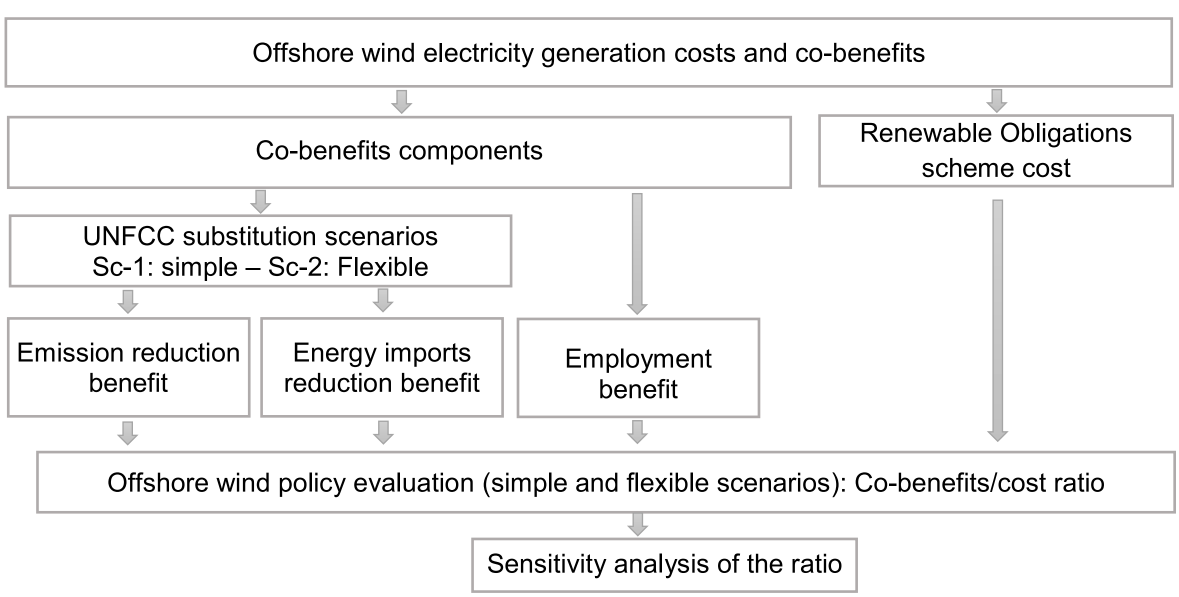

Fig. 2. Methodological approach for assessing co-benefits and policy evaluation under two substitution scenarios.

Although the RO scheme closed in March 2017, approved generators will continue to receive the revenue from ROCs until March 2037, or for 20 years, whichever comes sooner (Shao et al., 2022; Woodman and Mitchell, 2011).

Fig. 3 indicates the ROC buyout costs as set by Ofgem. Fig. 3 also shows the reported ROC prices in monthly market auctions, as and when reported. Whilst coverage of ROC market auction prices is not comprehensive, we can observe that these prices are roughly guided by the buy-out price. We therefore use buy-out price for our analysis, and the observed difference between auctioned market prices and buy-out prices informs our sensitivity analysis.

The RO scheme cost for offshore wind is determined by considering the quantity of issued ROCs and the corresponding buyout price as follows:

$$C_{G,t} = \sum\nolimits_{t} (Q_{ROCs,t} * P_{B,t}) \tag{1}$$

Which $C_{G,t}$ is the cost of ROCs scheme (£mn), $Q_{ROCs,t}$ is the number of issued offshore wind ROCs (mn), and $P_{B,t}$ buyout price at year t (£mn/ROC).

2.2. Emission reduction assessment

Emission reduction from offshore wind generation is derived from multiple methods and sources. Some studies adopt a *marginal emissions method*, which projects future GHG emission scenarios from the electricity generation pathway (Hawkes, 2010, 2014). Other studies utilise the UNFCCC framework to determine emission factor for the displacing electricity generated by fossil-fuels within an electricity system (Burgos-Payán et al., 2013; Yousuf et al., 2014).

In this analysis we employ the UNFCCC framework to quantify the emission reduction resulting from the integration of wind energy development (Ortega et al., 2013b; UNFCCC, 2009). The UNFCCC framework provides various scenarios of emission reduction, considering the possible displacement of existing electricity capacity with new renewable energy sources. Displacement could target all existing fossil-fuel powered capacity whether they are operating as baseload electricity generation or not, as well as any of the most recent non-renewable energy plants. Thus, this framework encompasses three key factors to cover all possible displacement including: Operating Margin (OM), Build Margin (BM), and Combined Margin (CM).

The OM emission factor can be categorised into 'simple', or 'flexible', based upon whether electricity generation technologies are included or excluded. For the 'simple' OM, all existing power plants are excluded, except for low-cost/must-run power plants (i.e. nuclear and hydroelectric in this research). The 'flexible' OM considers the CO_2 emissions factor of all existing power plants. This differentiation is driven by the type of power generation that wind replaces. In the past, comparatively low levels of wind penetration replaced flexibly operating power plants (i.e., on the margins), not affecting nuclear and run-off river hydroelectric. In the future, higher shares of wind on the system could potentially replace nuclear and hydroelectricity under scenarios of nuclear capacity decommissioning (Carrara, 2020). We chose to compute both factors to future-proof the assessment. That said, both OM emissions factors are converging as the overall energy system decarbonises over time.

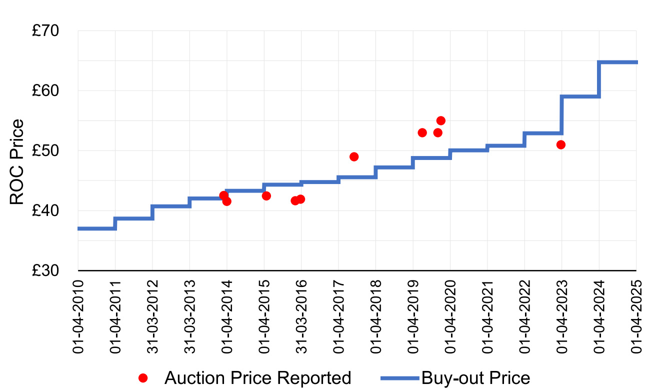

Fig. 3. ROC buy-out costs (blue line) against reported market prices (red dots). The normalise root mean square error (nRMSE) is 7.01% around the periodically set buy-out price set by Ofgem (Ofgem, 2015, 2016, 2020, 2024). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The BM emission factor considers all power plants during the most recent year and how their construction would be influenced by the introducing of offshore wind (UNFCCC, 2009). In order to calculate the BM, we assume that if offshore wind had not implemented, the gas plant would have been supplied by a combined cycle gas turbine' (CCGT) plant (Bean et al., 2017).

The margin emission factor is determined as the weighted average CO_2 emissions per MWh as follows (Yousuf et al., 2014):

$$EF_{M,t} = \sum\nolimits_{m} \frac{EG_{m,y}.EF_{m,y}}{\sum EG_{m,y}} \tag{2}$$

Where $EF_{M,t}$ represents margin factor for either OM or BM (t_{CO2}/MWh), $EF_{m,y}$ is the emission factor (t_{CO2}/MWh), and $EG_{m,y}$ is the electricity generation of technology m(MWh). $EF_{m,y}$ is the CO_2 emission factor of technology m, and $EG_{m,y}$ denotes net electricity generation by technology m in the year y. $EF_{m,y}$ is the CO_2 emission factor of technology m, which Technology m in this study encompasses three main source of electricity emissions from coal, oil, and natural gas. The equivalent emission ($EF_{m,y}$) for coal, oil, and natural gas technology were considered 336 kg_{CO2}/MWh, 285 kg_{CO2}/MWh, 186 kg_{CO2}/MWh, respectively (UK Government, 2023).

The CM factor is determined as a weighted average of both the OM and BM factors. Two distinct CM factors have been introduced, each based on the consideration of 'simple' and 'flexible' OM, respectively, as follows:

$$EF_{CM-simple} = W_{OM}EF_{OM-\ simple} + W_{BM}EF_{BM} \tag{3}$$

$$EF_{CM-flexible} = W_{OM}EF_{OM-\ flexible} + W_{BM}EF_{BM} \tag{4}$$

$EF_{CM-simple}$ and $EF_{CM-flexible}$ represents the CM emission factors for the simple and the flexible OM, respectively. $EF_{OM-\ simple}$ denotes the emission factor for simple OM, and $EF_{OM-flexible}$ is the emission factor for flexible OM. EF_{BM} represents the BM emissions factor. W_{OM} corresponds to the weighting of operating margin (%) and W_{BM} is the weighting of build margin (%) in the assessment. Following guidelines set forth by the IPCC for wind and solar power generation project activities, W_{OM} and W_{BM} are assigned equal values of 0.5 (UNFCCC, 2009). Finally, the emission reduction benefits of offshore wind power generation are evaluated by multiplying the marginal emissions factor (as described in Eq. (3) and (4)), and wind energy generation (TWh), and the carbon price (£/t_{CO2}) as follows:

$$B_{E-simple=}EF_{CM-simple} * Q_{G,t} \tag{5}$$

$$B_{E-flexible=}EF_{CM-flexible} * Q_{G,t} \tag{6}$$

$B_{E-simple}$ and $B_{E-flexible}$ represent emissions reduction benefits of offshore wind power generation through ROCs scheme (£bn), and $Q_{G,t}$ is the electricity generation through ROCs scheme (TWh).

2.3. Employment benefit assessment

In labour economics theory, the wage of newly employed individuals is equivalent to the opportunity cost of labour (Tourkolias and

Mirasgedis, 2011). However, employment provides additional social value beyond wages including the enhancement of life satisfaction and associated positive externalities. Conversely, unemployment can damage individual health, and increase the rate of negative social impacts including rising levels of substance misuse, crime and antisocial behaviour (Bartik, 2012; Brand, 2015). Consequently, the assessment of the social benefit of employment therefore involves considering two main components: first, the wage as the opportunity cost of labour, and second, the additional social benefits that arise from increasing employment (and hence decreasing unemployment).

The opportunity cost of labour varies depending on whether a newly employed person was previously employed or unemployed (Tourkolias and Mirasgedis, 2011). For individuals who were previously unemployed, the opportunity cost includes the loss of individual income (including in the UK universal credit). Conversely, for those who displace their previous job with new employment, the opportunity cost is the wage they were received in the previous job (including potential in-work benefits). Furthermore, the value of free time and leisure time for an unemployed person represents an additional component of the opportunity cost of labour. Upon gaining employment, there is a consequence of losing time for caring responsibilities for children and family members, recreation, or other socially-positive activities including voluntary work (Rojek, 2009; Tourkolias and Mirasgedis, 2011). To encompass most of these factors, the following equation is adapted (Mirasgedis et al., 2014):

$$B_E = EF_d * EF_{Id} * Q_{C,t} * [P * (WG_n - I_0 - L + S) + (1 - P) * (WG_n - WG_0)] \quad (7)$$

B_E represents the employment benefits (£mn), EF_d signify the offshore wind direct employment factor (job/MW), EF_{Id} represent offshore wind indirect and employment factor (job/MW). The number of fossil fuel jobs is subtracted from EF_d and EF_{Id} to capture net employment impact.

$Q_{C,t}$ denotes offshore wind energy capacity (GW). P reflects the probability of a newly employed person who was previously unemployed and $(1 - P)$ shows the probability that a newly employed person is moving from another existing job. To calculate the value of P, we have used the distribution curve proposed by (Haveman and Krutilla, 1967), which is demonstrated in Fig. 4. The range of P lies from 0 to 1. When unemployment rate of the economy is close to the natural rate of unemployment (usually around 5%), P equals 0. In contrast, if the unemployment rate is significantly high (usually exceeding 25%) then P approaches a value close to 1 implying that most newly employed individuals were previously unemployed (Tourkolias et al., 2009).

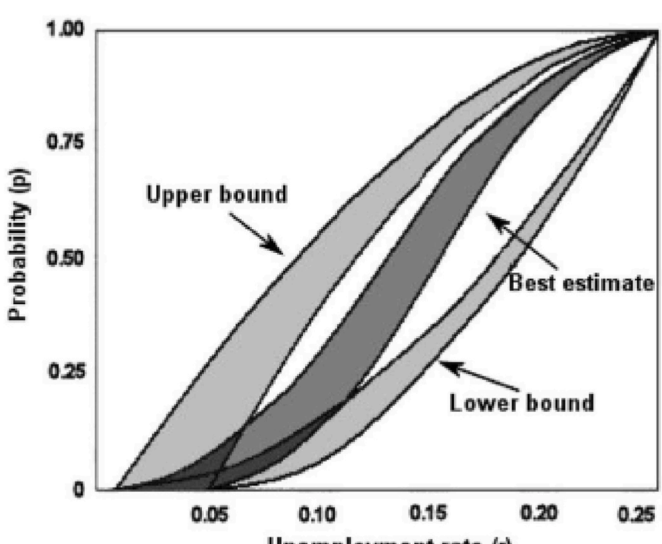

Fig. 4. Distribution of the probability of new worker to be drawn from idle pool- (Haveman and Krutilla, 1967).

WG_n and WG_0 represent the worker's wage in the new job and previous job, respectively. I_0 denotes the potential income of new worker when they were unemployed and $WG_n - I_0$ is defined as an 'earnings gap' between the current job and previous individual income which is influenced by factors such as education and working experiences (Xue et al., 2014). L stands for the value of leisure (though note that this also includes non-waged work including volunteering) time. The value of leisure time is associated with experiencing wellbeing during unemployment time. This value can be explored through cognitive factors, such as cognitive (quality of life) and effective (subjective well-being (SWB) aspects of life. S represents the value of health-related outcomes linked to being unemployed, including negative mental health impacts, poverty-related ill health, and harms to interpersonal wellbeing.

2.4. Avoided energy import benefit assessment

Reducing the import of energy resources represents a key step towards bolstering energy security. Improved energy security leads to better accessibility, reliability, and affordability of energy, thereby contributing progress towards Sustainable Development Goal 7. Energy security can be described as the uninterrupted accessibility of energy sources at an affordable price. Evaluating energy security value involves considering various factors related supply and demand (Glynn et al., 2017).

The energy security assessment methods predominantly involve the indicators that provide ratios to understand the trend of energy security in which it is non-monetary value for energy security. Those indicators notably encompass the diversity index HHI (Hirschman-Herfindahl Index (HHI)), the IEA's energy security index, and mean variance portfolio theory (Chuang and Wen, 2013; Kruyt et al., 2009; Sovacool and Mukherjee, 2011).

Greene and Leiby (2006) and Leiby (2007) introduced the energy security metric model to measure the energy security of USA by breaking down the energy insecurity impact into 'transfer of wealth', 'economic surplus losses', and 'macroeconomic disruption costs. Additionally, (Ortega et al., 2013b) has introduced another approach to monetise the energy security by using the concepts of trade balance and avoiding energy import expenses. Given the aim of the research to monetise the energy security benefits, the trade balance approach has been developed. The trade balance is equal to the total import avoidance which is assessed through multiplying energy price factors and equivalent imports that would have been required if offshore wind energy development were not utilised as following:

$$\text{Avoided energy import}_{simple} = PF_{CM-simple} * FF_{CM-simple} * Q_{G,t} \quad (8)$$

$$\text{Avoided energy import}_{flexible} = PF_{CM-flexible} * FF_{CM-flexible} * Q_{G,t} \quad (9)$$

$PF_{CM-simple}$ and $PF_{CM-flexible}$ denotes the margin price factor in £/TWh. Following the UNFCCC approach, price factors were calculated in a manner as per Eqs. (2)–(4), involving the substitution of the emissions factor with price factor. Subsequently, $EF_{m,y}$ was replaced with $PF_{m,y}$ for coal, oil, and natural gas import price in Eq. (2). to calculate OM and BM price factors. $FF_{CM-simple}$ and $FF_{CM-flexible}$ are marginal fuel conversion factors which represent the amount of primary energy avoided by developing offshore wind development (TJ/TWh). Fuel factors was calculated as per Eqs. (2)–(4), firstly by substitution of the emissions factor ($EF_{m,y}$) with the fuel factor ($FF_{m,y}$) for avoided coal, oil, and natural gas in Eq. (2) and subsequently calculation for OM and BM for fuel factors.

The rise in offshore wind generation reduced the need for energy imports, however, though wind turbine manufacturing has grown in the UK, it remains reliant upon technology imports (Crabtree et al., 2015), particularly from the Netherlands and Denmark (Zhao et al., 2023). This implies that as offshore wind energy capacity increases, so does the overall expense of importing turbines. Consequently, greater energy self-sufficiency is accompanied by increased dependency on turbine imports. To address this, Eq.(8) and (9) has been adjusted by subtracting turbine import expense from energy import expenses. To estimate the import expenses of turbine, the Levelised Cost of Electricity (LCOE) concept has been applied as follows:

$$\text{Turbine import expenses} = 0.3 * 0.5 * 0.57 * LCOE_{G,t} * Q_{G,t} \tag{10}$$

Here, 0.3 signifies the proportion of full turbine expenses in LCOE (Crabtree et al., 2015), 0.5 presents the percentage of importing out of full turbine expenses (Johnston et al., 2020). additionally, 0.57 indicates the portion of ROCs contract operation (20 year) out of 35 years average offshore wind lifespan, $LCOE_{G,t}$ stands for LCOE of offshore wind (MWh). Finally, the avoided energy import benefits associated with offshore wind electricity generation for simple ($B_{I-simple}$), and flexible ($B_{I-flexible}$) scenarios are assessed by deducting Eq (10) from Eq.(8) and (9).

3. Results

3.1. Renewable Obligations certificate costs

Table 1 displays the buy-out prices and the number of ROCs associated with offshore wind from 2009 to 2022. The ROCs scheme was initially introduced in 2002, but the number of ROCs accredited for offshore wind was negligible before 2009. Consequently, this study focuses on the period from 2009 to 2022. The number of ROCs issued for offshore wind has experienced a remarkable surge from 2.7 in 2009 to 45.6 million in 2022. To assess the expense of ROCs, Eq. (1) is applied, which involves multiplying the number of ROCs by the buy-out price. The cost of offshore wind ROCs has notably risen by 10 times from 2010 to 2022, while electricity generation has seen a six-fold increase during the same period. The trend of ROCs costs results with ±20% sensitivity to cost variation is shown in Fig. 5.

3.2. Emission reduction benefit

Table 2 illustrates the climate benefits of offshore wind electricity generation under the CM ‘simple’ and ‘flexible’ options. The emission factors for both options have declined from 2009 to 2022, corresponding to the decline in total electricity generation emission from 150 Mt_{CO2} in 2009 to 54 Mt_{CO2} in 2022 (ONS, 2023a). To assess monetary value of emission reduction benefits, we incorporate the UK shadow price of carbon. This price represents the social benefit of abating a tonne of carbon or the social cost associated with emitting a marginal tonne of carbon (Dietz, 2007). The shadow price serves as a metric to gauge the emissions impact resulting from policy intervention (Cui et al., 2022; Drèze and Stern, 1990; Price et al., 2007). The shadow price in the UK started at £51/t_{CO2} in 2009 and gradually increased to £62/t_{CO2} in 2022 (Department of Energy and Climate change, 2011).

The total benefit from emission reduction exhibited an upward trend for both the simple and flexible options, attributed to the growing number of new offshore wind capacities. The emissions benefit has fluctuated around £400mn since 2015. Throughout the entire period, the emissions reduction benefits amounted to £4.4 ± 0.9bn and £3.9 ± 0.8bn for simple and flexible options, respectively. The reduction benefits for the simple emissions factors were slightly higher than the flexible option due to higher emissions factor associated with simple OM compared to flexible OM. The trend of emission reduction benefit (simple scenario) with ±20% sensitivity to variation of shadow price of carbon depicted is in Fig. 6.

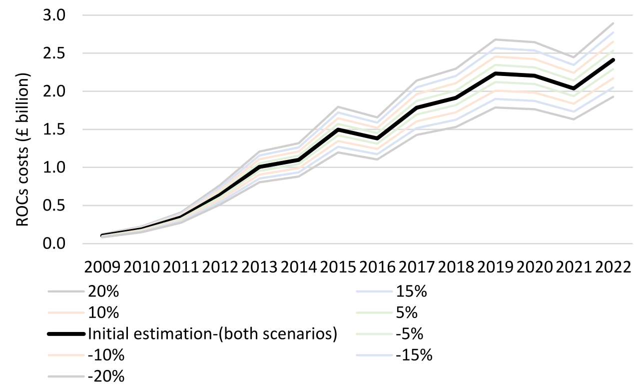

Fig. 5. ROCs costs with ±20% sensitivity to cost variation.

3.3. Employment benefit

To evaluate employment-related social benefits, we computed the P value using UK unemployment rate data (Table 3). The UK unemployment rate has fluctuated ranging from 3.7% to 8.1% during 2009–2022. Correspondingly, the P value has varied between 0.01 and 0.15, respectively. Here we draw directly from labour economics considerations.

Offshore wind energy has significantly contributed to job creation in the UK by supporting 15,205 direct jobs and 10,888 indirect jobs to 2020; with rises to 19,591 and 11,491, respectively in 2021 (OWIC, 2022). This implies an average of 1.6 and 1.03 direct and indirect employment factors per MW (Aura, 2017). To estimate the net employment impact, offshore wind job factors subtracted by direct employment factor of gas plant in the UK which is considered at 0.3 (Bryan et al., 2017)

As per Eq. (7), the value of GW_n is assumed to be £38,500 per worker in 2022 based on the average salary for roles such as: wind turbine or electrical technician, offshore drilling worker, and marine engineer positions (NCS, 2023). This salary benchmark was discounted by 5% annually to adjust the salary level from 2009 to 2021 (Table 4). L and I_0 are assumed to be 15% and 30% of total salary, respectively. Additionally, GW_0 is considered to be15% lower than GW_n (Mirasgedis et al., 2014).

By the above assumptions, the total employment-related social benefit through the ROC scheme shows an increasing trend amounting to £1bn±0.2 during 2009–2022, primarily driven by the growth in offshore wind energy generation capacity, leading to a gradual rise in overall employment and social benefits stemming from the industry (Fig. 7.).

Table 1
The ROCs scheme costs attributed to offshore wind generators.

Period	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
No. ROCs (million)	2.7	5.0	8.8	15.7	23.9	25.4	33.8	30.8	38.9	40.3	45.7	44.1	40.1	45.6
Buy-out price (£/ROC)	37	37	39	41	42	43	44	45	46	47	49	50	51	53
ROC costs- (£bn)	0.1	0.2	0.3	0.6	1.0	1.1	1.5	1.4	1.8	1.9	2.2	2.2	2.0	2.4

Ref (Ofgem, 2023):

Table 2
Emission reduction benefit.

period	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Emission factors (t_{CO2}/MWh)														
$EF_{CM-simple}$	0.48	0.48	0.47	0.51	0.49	0.46	0.42	0.36	0.34	0.33	0.30	0.29	0.30	0.29
$EF_{CM-flexible}$	0.42	0.43	0.42	0.44	0.43	0.40	0.36	0.32	0.31	0.30	0.28	0.27	0.28	0.27
Emission benefits (£mn)														
$B_{E-simple}$	67	83	133	239	344	341	417	333	403	404	430	409	385	396
$B_{E-flexible}$	59	74	117	207	300	300	366	297	362	368	399	383	361	372

Ref: authors calculation.

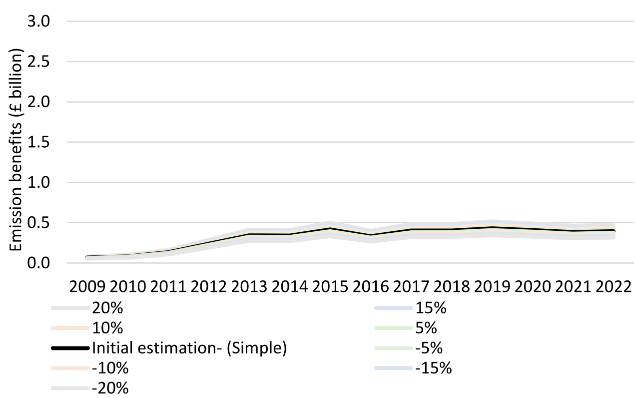

Fig. 6. Emission reduction benefit (scenario: simple) with ±20% sensitivity to variation of shadow price of carbon.

3.4. Energy import avoided benefit

To assess the energy import-avoided benefits, we have incorporated international oil prices, along with UK import prices for coal and natural gas to construct the price factor. The exchange rate parity report from (ONS, 2023c) was applied to standardize all currencies to sterling (£). Moreover, to ensure uniformity in energy unites, 1 tonne of natural gas, oil, and coal is converted to 1.1, 41.9, and 27 GJ, respectively, (Defra, 2012). Subsequently, the energy price ($PF_{m,y}$), is converted to the price factor as per Eqs. (3) and (4) and detailed in Table 5.

To estimate the fuel conversion factor, the initial step involves calculating the fuel usage ($FF_{m,y}$) across UK power plants. As shown in Table 6, coal-based electricity generation becomes less efficient whilst natural gas and oil-based become slightly more efficient over time, based on the fuel usage (in TJ) for each TWh of electricity produced. $FF_{m,y}$ converted to the fuel conversion factor, incorporates all three fuels (coal, oil, and natural gas) as per Eqs. (3) and (4). As expected, the simple fuel factor surpasses the flexible fuel factor, indicating that the simple approach excludes low-cost/must-run power plants, resulting in lower total generation and a subsequently higher factor.

As per Eqs. 8–10, and the price and fuel factors (Tables 5 and 6), evaluation of avoided energy imports is assessed and reported in Table 7. Avoided energy imports reached a record in 2022, predominantly influenced by significant surged prices in 2022 during the period of Russian invasion of Ukraine and subsequent gas demand and supply fluctuation in the face of economic sanctions (Q. Zhang et al., 2023), combined with the resurgence of global manufacturing through China's slow lifting of COVID-19 restrictions (D. Zhang et al., 2023).

To incorporate turbine import expenses, the average of LCOE as per (Aldersey-Williams et al., 2019; Jennings et al., 2020; Smart, 2016) has been considered. The trend of turbine import expenses is affected by the

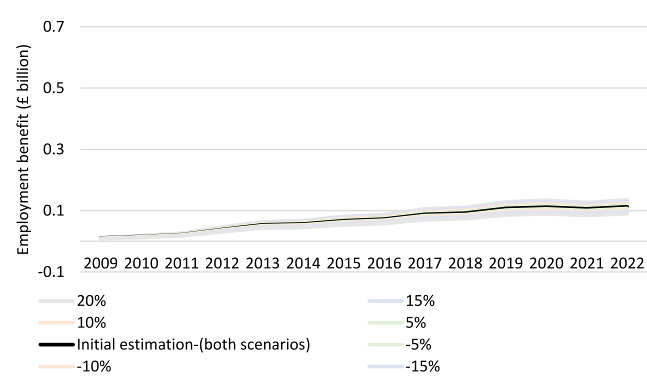

Fig. 7. Employment benefit with ±20% sensitivity to employment salary variation.

Table 3
Unemployment rate and P value.

Period	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Unemployment rate %	7.6	7.9	8.1	8	7.6	6.2	5.4	4.9	4.4	4.1	3.8	4.6	4.5	3.7
P	0.12	0.14	0.15	0.14	0.12	0.07	0.04	0.03	0.02	0.01	0.01	0.02	0.02	0.01

Ref: (ONS, 2023b) and authors calculation.

Table 4
Employment and job creation social benefit.

Period	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Direct jobs (k)	1.5	2.0	2.7	4.5	6.1	6.7	7.9	8.3	9.7	9.8	10.9	10.5	9.6	9.9
Indirect jobs (k)	1.0	1.3	1.7	2.9	3.9	4.3	5.1	5.3	6.3	6.3	7.0	6.8	6.2	6.4
Total net jobs (k)	2.2	2.9	3.9	6.6	8.9	9.7	11.5	12	14.2	14.2	15.9	15.4	13.9	14.5
Salary (k£/year)	20.4	21.4	22.5	23.6	24.8	26.1	27.4	28.7	30.2	31.7	33.3	34.9	36.7	38.5
B_E (£mn)	12	18	25	44	60	64	76	82	99	104	121	126	119	127

Ref: authors calculation.

Table 5
Energy import price factor.

Period	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Energy import price ($PF_{m,y}$) -(£/MWh)														
Coal	7	8	11	9	8	8	6	7	10	10	8	8	18	36
Oil	23	36	46	50	46	42	28	25	32	40	42	35	47	79
Natural gas	18	17	21	23	24	20	14	11	14	19	12	8	38	105
Price factor (£/MWh)														
$PF_{CM-simple}$	15	15	18	18	18	15	11	9	11	14	9	6	28	77
$PF_{CM-flexible}$	14	14	17	17	17	14	10	8	10	13	9	6	27	73

Ref: (DESNZ, 2023c; World Bank, 2023) and author calculation.

Table 6
Fuel conversion factor.

Period	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Fuel usage for fossil fuel-based power plants ($FF_{m,y}$)- (TJ/TWh)														
Coal	10	10	10	10	10	10	10	10	10	11	11	11	11	11
Oil	11	10	11	11	12	12	12	12	13	18	8	9	9	9
Natural gas	8	8	8	8	8	8	8	7	8	7	7	8	7	7
Fuel conversion factor -(TJ/TWh)														
$FF_{CM-simple}$	7.8	7.8	7.6	7.8	7.6	7.3	6.8	6.5	6.2	6.0	5.7	5.5	5.7	5.5
$FF_{CM-flexible}$	7.0	7.1	6.8	7.0	6.8	6.6	6.1	5.8	5.7	5.5	5.3	5.2	5.3	5.2

Ref: (DESNZ, 2023a) and author calculation.

Table 7
Energy import benefit.

Period	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Avoided energy import - (£mn)														
Avoided energy $import_{simple}$	92	110	207	349	503	416	374	261	409	513	360	217	941	2609
Avoided energy $import_{flexible}$	75	92	169	287	416	346	308	213	339	434	311	192	834	2328
Turbine import expenses														
LCOE (£/MWh)	123	128	121	122	138	109	114	111	97	85	81	77	72	68
ROCs- generation (TWh)	3	3	5	9	13	14	18	16	21	21	24	23	21	22
Turbine import expenses (£mn)	25	31	47	77	128	106	146	129	144	130	139	128	109	107
Energy import benefit- (£mn)														
$B_{I-simple}$	66	80	161	272	375	310	228	132	266	383	220	90	832	2502
$B_{I-flexible}$	50	62	122	210	288	240	162	84	195	304	172	64	725	2221

Ref: authors calculation.

upward renewable electricity generation trend and a simultaneous decrease in LCOE. Energy import benefit demonstrates an overall increasing trend, except for 2019 and 2020, due to the diminishing share of oil and coal in electricity generation, which in turn affects emissions factors. The total benefit amounted to £5.9 ± 0.3bn and £4.9 ± 0.3bn in simple and flexible options, respectively (Fig. 8.).

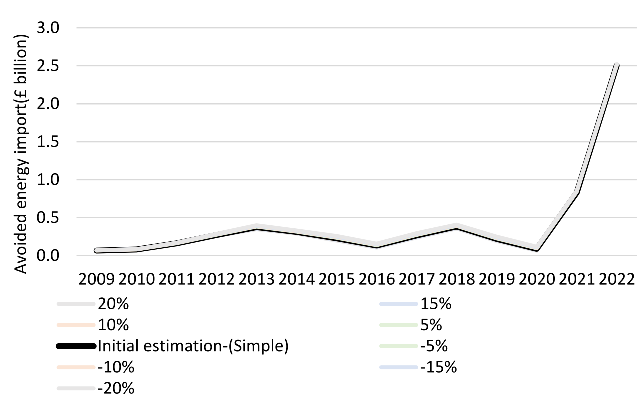

Fig. 8. Avoided energy import with sensitivity to LCOE variation.

4. Discussion

This research has assessed the co-benefits associated with offshore wind energy development to better integrate sustainability in evaluation of the Renewable Obligation (RO) certification scheme: the UK's flagship support scheme until 2017, and to date, the biggest contributor to the UK's offshore wind fleet. We find that offshore wind energy presents a range of co-benefits for the energy system, as well as socio-economic and environmental benefits, which require deep consideration by policymakers in future energy policy scenarios.

Our research finds that the performance of the RO scheme is heavily dependent on evaluating their sustainability co-benefits. We have identified three significant sustainability co-benefits to offshore wind energy generation in the UK specifically: (1) emissions reduction, (2) decreased dependency on energy imports, and (3) increased employment opportunities.

In relation to (1): our analysis demonstrates significant benefits in reducing emissions, specifically an existing £4.4 ± 0.9bn and £3.9 ± 0.8bn of climate benefit in the simple and flexible scenarios. By considering carbon shadow price as £51–62/t_{CO2}, with considering ±20% variation in carbon price.

In relation to (2) offshore wind energy increases the energy supply and is directly replacing fossil generation, providing a meaningful contribution to ensuring domestic energy security, and reducing the need for energy imports. This is an issue of growing importance given ongoing geopolitical concerns over oil pricing and availability in the wake of Russia's invasion of Ukraine (Höysniemi, 2022; Prisecaru, 2022). However, as offshore wind generation rises, the demand for import of the equipment particularly turbine increases, thereby compromising a portion of energy security. Our findings indicate that offshore wind could notably reduce the need for energy imports by £7.4bn and £6.4bn in the simple and flexible scenarios, respectively. However, considering the projected £1.4 ± 0.3bn expense for turbine imports, the net benefit becomes £5.9 ± 0.3bn and £4.9 ± 0.3bn in simple and flexible scenarios.

In relation to (3) the development of offshore wind energy in the UK has resulted in the creation of over 31,000 new direct and indirect jobs which contributes significantly to social benefits by £1.0 ± 0.2bn associated with wealth generation in regional economies. The extent of employment and job creation social benefits is strongly influenced by local and national economic circumstances, such as the current employment rate, but nevertheless contributes to a *just* transition for communities replacing fossil fuel-based employment with that funded through offshore wind energy expansion.

The total benefits of offshore wind energy are shown as £11.3 ± 0.8bn and £9.8 ± 0.7bn in the simple and flexible scenarios, respectively.

A breakdown shows that the avoided import, emissions reduction, and employment generated £5.9 ± 0.3bn, £4.4 ± 0.9bn, and £1.0 ± 0.2bn, of co-benefits respectively in simple scenario. While in the flexible scenario it would be £4.9 ± 0.3bn, £3.9 ± 0.8bn, and £1.0 ± 0.2bn, respectively. The trend of costs and benefits is depicted in Fig. 9. The cost of ROCs was higher than the sustainability co-benefits. The benefits from import reduction surged due to high energy prices in 2021 and 2022. The cost of ROCs was £18.8 ± 3.8bn during 2009–2022. However, the policy supporting cost is expected to decline due to reduction in cost of technology as cumulative capacity increases (i.e. the learning curve) in future (Lecca et al., 2017).

Sensitivity analysis of findings has been conducted across the highly uncertain assumptions within each cost and co-benefit category.

Results showed that a 20% variation in ROCs costs, labour cost, carbon price, and labour salary could result in co-benefit coverage of costs ranging from 50% to 75% in simple scenarios and 43%–65% in flexible scenarios (Fig. 10).

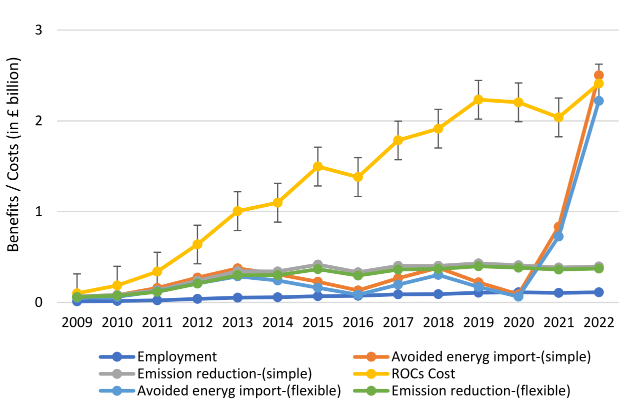

Fig. 9. Offshore wind energy policy costs and benefits trends under two simple and flexible scenarios.

The sensitivity analysis results show that co-benefits/cost ratios rise as ROCs cost falls. For instance, in a simple scenario in which the initial ratio amounted 60%, reduction in ROCs costs by 10%, and 20% would rise the co-benefits/cost ratio to 63%, and 75%. Conversely, a 10%, and 20% increase in ROCs costs lowers the ratio to 52%, and 50%. On average, a 1% change in ROCs cost results in a 0.6% change in the co-benefits/cost ratio in the simple scenario and a 0.53% change in the flexible scenario.

Additionally, variation in the shadow price of carbon leads to a 0.23% and 0.21% variation of the co-benefits/cost ratio for simple and flexible scenarios, respectively. The sensitivity variation to a 1% change in LCOE and employment salary is 0.8 and 0.5, respectively in both scenarios.

The sensitivity results show that the efficiency of the ROCs policy is most affected by the cost of ROCs, followed by the shadow price of carbon, and is least affected by the employee salary in both scenarios. This indicates the importance of both designing a cost-effective offshore wind supporting policy scheme, alongside careful governmental management of the shadow price of carbon.

We demonstrate that support for renewable energy through ROCs offers numerous co-benefits aligned with the UN Sustainable Development Goals (SDGs), which can be quantified monetarily, leading to better understanding of their positive socio-environmental impact. Electricity from offshore wind addresses several critical global sustainability challenges such as promoting good health and reducing emissions relevant to UN SDG13 (Biber-Freudenberger et al., 2020). Employment benefits associated with offshore wind energy capacity are linked to SDG8 (decent work and economic growth) which is crucial for overall success of all SDGs. Additionally, access to affordable, reliable and low-carbon energy services are the main targets of SDG7 (McCollum et al., 2017). Moreover, the offshore wind energy activities including installation, operation, and maintenance (O&M), and decommissioning may have negative environmental impact that should be considered in future research.

5. Conclusion and policy implications

The benefits and costs of offshore wind energy policy are currently being re-evaluated in the UK. Recent challenges to the UK government's CfD auction scheme highlight the importance of industry's concerns over increasing costs in the overall sustainability of the sector. Decisions on offshore wind energy planning and implementation are driven by multiple factors including: legally binding climate change mitigation commitments, the politics of land use and social opposition to different

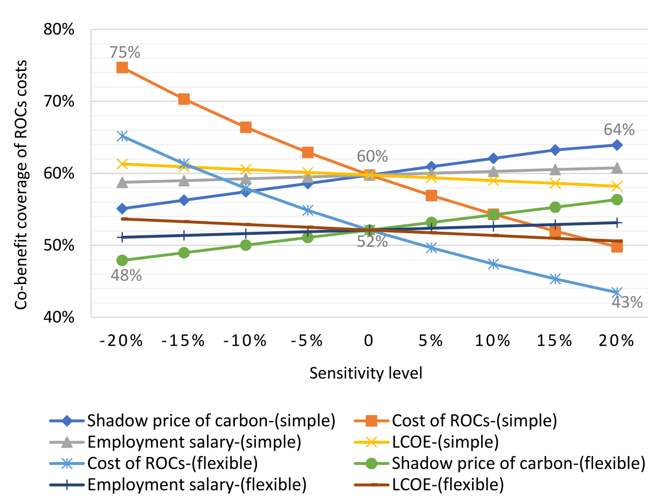

Fig. 10. Sensitivity analysis of co-benefit coverage of cost of offshore wind ROCs costs.

energy technologies (including onshore wind and solar energy), and geopolitical risks to energy systems including price shocks to oil and gas markets (e.g. the European energy crisis beginning in 2021 following Russia's invasion of Ukraine). The RO scheme was initially phased out by the UK government to be replaced by the seemingly more efficient CfD scheme. However, the recent challenges to the CfD scheme, alongside our examination of the RO scheme benefits – 5 years after its closure to new applications – reveals the scope of potential socially-beneficial outcomes of the RO policy, and the importance of ensuring continued political support for offshore wind energy in the face of industry scepticism over the price point for offshore wind generation.

Under the RO scheme, generators benefit from high wholesale electricity prices, which was ultimately one of the arguments that led to the phase-out. While the RO scheme has been traditionally associated with higher costs, this cost profile may not continue, as wholesale energy prices remain above pre-COVID-19 crisis prices. Monetising costs and whole societal benefits associated with offshore wind energy deployment enables policymakers to assess the efficacy of offshore wind policy in the round. This study first identified the most significant sustainability co-benefits associated with offshore wind energy and then assessed the effectiveness of ROCs in the UK. This analysis could be applied to other policy schemes, including the UK's current CfD scheme, but also on a global scale to a variety of quota-based policy schemes in which broader non-price related sustainability co-benefits do not receive enough attention from policy authorities in the formulation of energy policy strategy. Offshore wind energy can potentially offer numerous sustainability co-benefits including GHG emissions reduction, energy security increases, and employment expansion. Ascribing monetary value to these sustainability co-benefits creates a powerful tool for decision-making on wind energy deployment relative to fossil fuel and nuclear alternatives. The evaluation of sustainability co-benefits allows gaining a deeper understanding of wind projects beyond the direct market pricing. The findings are therefore directly applicable to energy systems that have supported, or are supporting, renewables deployment using quotas systems similar to the UK's RO certification scheme.

CRediT authorship contribution statement

Vahid Ghorbani Pashakolaie: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Matthew Cotton:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Malte Jansen:** Writing – review & editing, Writing – original draft, Validation, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

None of the authors have any conflicts of interest (financial or otherwise) to report. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

Adom, P.K., Amuakwa-Mensah, F., Agradi, M.P., Nsabimana, A., 2021. Energy poverty, development outcomes, and transition to green energy. Renew. Energy 178, 1337–1352.

Aldersey-Williams, J., Broadbent, I.D., Strachan, P.A., 2019. Better estimates of LCOE from audited accounts–A new methodology with examples from United Kingdom offshore wind and CCGT. Energy Pol. 128, 25–35.

Allan, G.J., Ross, A.G., 2019. The characteristics of energy employment in a system-wide context. Energy Econ. 81, 238–258.

Ambrose, 2023. What Went Wrong at UK Government's Offshore Wind Auction? Theguardian.

Aura, 2017. Future UK Employment in the Offshore Wind Industry. Cambridge Econom, pp. 1–17.

Bartik, T.J., 2012. Including jobs in benefit-cost analysis. Annu. Rev. Resour. Econ. 4, 55–73.

Bean, P., Blazquez, J., Nezamuddin, N., 2017. Assessing the cost of renewable energy policy options–A Spanish wind case study. Renew. Energy 103, 180–186.

BEIS, 2022. Major acceleration of homegrown power in Britain's plan for greater energy independence. https://www.gov.uk/government/news.

Beiter, P., Guillet, J., Jansen, M., Wilson, E., Kitzing, L., 2024. The enduring role of contracts for difference in risk management and market creation for renewables. Nat. Energy 9, 20–26.

Biber-Freudenberger, L., Ergeneman, C., Förster, J.J., Dietz, T., Börner, J., 2020. Bioeconomy futures: expectation patterns of scientists and practitioners on the sustainability of bio-based transformation. Sustain. Dev. 28, 1220–1235.

Blyth, W., Associates, O.E., Gross, R., Rickman, J., 2023. Transition Risk: Investment Signals in a Decarbonising Electricity System.

Brand, J.E., 2015. The far-reaching impact of job loss and unemployment. Annu. Rev. Sociol. 41, 359–375.

Bryan, J., Evans, N., Jones, C., Munday, M., 2017. Regional electricity generation and employment in UK regions. Reg. Stud. 51, 414–425.

Burgos-Payán, M., Roldán-Fernández, J.M., Trigo-García, Á.L., Bermúdez-Ríos, J.M., Riquelme-Santos, J.M., 2013. Costs and benefits of the renewable production of electricity in Spain. Energy Pol. 56, 259–270.

Carrara, S., 2020. Reactor ageing and phase-out policies: global and regional prospects for nuclear power generation. Energy Pol. 147, 111834 https://doi.org/10.1016/j.enpol.2020.111834.

CCC, 2020. The Sixth Carbon Budget– Electricity Generation. https://www.theccc.org.uk/.

Chuang, M.C., Wen, H., 2013. Energy security and improvements in the function of diversity indices — taiwan energy supply structure case study. Renew. Sustain. Energy Rev. 24, 9–20.

Cotton, M., 2019. Planning, infrastructure and low carbon energy. Companion to Environ. Plan. Sustain. S. Davoudi, Al., pp. 248–256.

Crabtree, C.J., Zappalá, D., Hogg, S.I., 2015. Wind energy: UK experiences and offshore operational challenges. Proc. Inst. Mech. Eng. Part A J. Power Energy 229, 727–746.

Cui, L., Dong, R., Mu, Y., Shen, Z., Xu, J., 2022. How policy preferences affect the carbon shadow price in the OECD. Appl. Energy 311, 118686. https://doi.org/10.1016/j.apenergy.2022.118686.

DECC, 2014. Implementing Electricity Market Reform (EMR). https://www.gov.uk/government/publications.

Defra, 2012. Guidelines to Defra/DECC's GHG Conversion Factors for Company Reporting. Defra London. https://www.gov.uk/government/collections.

Department of Energy and Climate change, 2011. Guidance on Estimating Carbon Values beyond 2050: an Interim Approach.

DESNZ, 2023a. Fuel Used in Electricity Generation and Electricity Supplied. https://www.gov.uk/government.

DESNZ, 2023b. CfD register. Low carbon contract. Co. Electr. Settlements Co. https://www.lowcarboncontracts.uk.

DESNZ, 2023c. Average prices of fuels purchased by the major UK power producers. https://www.gov.uk/government.

Di Cosmo, V., Valeri, L.M., 2018. Wind, storage, interconnection and the cost of electricity generation. Energy Econ. 69, 1–18.

Dietz, S., 2007. Review of DEFRA paper:"The social cost of carbon and the shadow price of carbon: what they are, and how to use them in economic appraisal in the UK. Dep. Environ. Farming Rural Aff. London 1–24.

Dinh, V.N., McKeogh, E., 2019. Offshore wind energy: technology opportunities and challenges. In: Proceedings of the 1st Vietnam Symposium on Advances in Offshore Engineering: Energy and Geotechnics. Springer, pp. 3–22.

Diógenes, J.R.F., Claro, J., Rodrigues, J.C., Loureiro, M.V., 2020. Barriers to onshore wind energy implementation: a systematic review. Energy Res. Social Sci. 60, 101337.

Drèze, J., Stern, N., 1990. Policy reform, shadow prices, and market prices. J. Publ. Econ. 42, 1–45.

Fujiwara, D., Campbell, R., 2011. Valuation Techniques for Social Cost-Benefit Analysis : Valuation Techniques for Social Cost-Benefit Analysis. Current.

Gil, H.A., Gomez-Quiles, C., Riquelme, J., 2012. Large-scale wind power integration and wholesale electricity trading benefits: estimation via an ex post approach. Energy Pol. 41, 849–859.

Glasson, J., Durning, B., Welch, K., Olorundami, T., 2022. The local socio-economic impacts of offshore wind farms. Environ. Impact Assess. Rev. 95, 106783.

Glynn, J., Chiodi, A., Ó Gallachóir, B., 2017. Energy security assessment methods: quantifying the security co-benefits of decarbonising the Irish Energy System. Energy Strategy Rev. 15, 72–88. https://doi.org/10.1016/j.esr.2016.11.005.

Green, R., Vasilakos, N., 2011. The economics of offshore wind. Energy Pol. 39, 496–502.

Greene, D.L., Leiby, P.N., 2006. The Oil Security Metrics Model: a Tool for Evaluating the Prospective Oil Security Benefits of DOE's Energy Efficiency and Renewable Energy R&D Programs. Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States).

Haveman, R., Krutilla, J., 1967. Unemployment, excess capacity, and benefit-cost investment criteria. Rev. Econ. Stat. 382–392.

Hawkes, A.D., 2014. Long-run marginal CO2 emissions factors in national electricity systems. Appl. Energy 125, 197–205.
Hawkes, A.D., 2010. Estimating marginal CO2 emissions rates for national electricity systems. Energy Pol. 38, 5977–5987.
Höysniemi, S., 2022. Energy futures reimagined: the global energy transition and dependence on Russian energy as issues in the sociotechnical imaginaries of energy security in Finland. Energy Res. Social Sci. 93, 102840.
IEA, 2023. Offshore Wind Capacity by Country, pp. 1991–2030.
IRENA, G., 2013. 30 Years of Policies for Wind Energy-Lessons from 12 Wind Energy Markets.
IRENA, I.R.E.A., 2022. Renewable Energy and Jobs - Annual Review 2021.
Jansen, M., 2023. Drax electric insights quarterly-Q2 2023. Q2 2023: offshore wind held up by the inflation storm. Elect. Insight Q.
Jansen, M., Beiter, P., Riepin, I., Müsgens, F., Guajardo-Fajardo, V.J., Staffell, I., Bulder, B., Kitzing, L., 2022. Policy choices and outcomes for offshore wind auctions globally. Energy Pol. 167, 113000.
Jansen, M., Staffell, I., Kitzing, L., Quoilin, S., Wiggelinkhuizen, E., Bulder, B., Riepin, I., Müsgens, F., 2020. Offshore wind competitiveness in mature markets without subsidy. Nat. Energy 5, 614–622.
Jennings, T., Tipper, H.A., Daglish, J., Grubb, M., Drummond, P., 2020. Policy, Innovation and Cost Reduction in UK Offshore Wind.
Johnston, B., Foley, A., Doran, J., Littler, T., 2020. Levelised cost of energy, A challenge for offshore wind. Renew. Energy 160, 876–885.
Kaldellis, J.K., Apostolou, D., Kapsali, M., Kondili, E., 2016. Environmental and social footprint of offshore wind energy. Comparison with onshore counterpart. Renew. Energy 92, 543–556.
Kitzing, L., 2014. Risk implications of renewable support instruments: comparative analysis of feed-in tariffs and premiums using a mean–variance approach. Energy 64, 495–505.
Kruyt, B., Van Vuuren, D.P., de Vries, H.J.M., Groenenberg, H., 2009. Indicators for energy security. Energy Pol. 37, 2166–2181.
Lecca, P., McGregor, P.G., Swales, K.J., Tamba, M., 2017. The importance of learning for achieving the UK's targets for offshore wind. Ecol. Econ. 135, 259–268.
Leiby, P.N., 2007. Estimating the Energy Security Benefits of Reduced US Oil Imports. Citeseer.
Li, J., Liu, G., Shao, J., 2020. Understanding the ROC transfer payment in the renewable obligation with the recycling mechanism in the United Kingdom. Energy Econ. 87, 104701.
Madlener, R., Myles, H., 2000. Modelling socio-economic aspects of bioenergy systems: a survey prepared for IEA Bioenergy Task 29. In: IEA Bioenergy Task. Citeseer.
McCollum, D., Gomez Echeverri, L., Riahi, K., Parkinson, S., 2017. Sdg7: Ensure Access to Affordable, Reliable, Sustainable and Modern Energy for All.
Mirasgedis, S., Tourkolias, C., Pavlakis, E., Diakoulaki, D., 2014. A methodological framework for assessing the employment effects associated with energy efficiency interventions in buildings. Energy Build. 82, 275–286.
NCS, 2023. Explore Careers. https://nationalcareers.service.gov.uk.
Ofgem, 2024. Renewables Obligation (RO) buy-out price, mutualisation threshold and mutualisation ceilings for 2024 to 2025. https://www.ofgem.gov.uk/publications/renewables-obligation-ro-buy-out-price-mutualisation-threshold-and-mutualisation-ceilings-2024-2025.
Ofgem, 2023. Renewables Obligation (RO). https://www.ofgem.gov.uk/.
ONS, 2023a. 2022 UK greenhouse gas emissions. https://www.gov.uk/government/publications.
ONS, 2023b. Unemployment rate. https://www.ons.gov.uk.
ONS, 2023c. Average Sterling exchange rate. https://www.ons.gov.uk/economy.
ONS, 2022. Wind Energy in the UK ons.gov.uk/economy/environmentalaccounts.
Ortega-Izquierdo, M., Del Río, P., 2016. Benefits and costs of renewable electricity in Europe. Renew. Sustain. Energy Rev. 61, 372–383.
Ortega, M., Del Río, P., Montero, E.A., 2013a. Assessing the benefits and costs of renewable electricity. The Spanish case. Renew. Sustain. Energy Rev. 27, 294–304.
Ortega, M., Del Río, P., Montero, E.A., 2013b. Assessing the benefits and costs of renewable electricity. the Spanish case. Renew. Sustain. Energy Rev. 27, 294–304.
OWIC, 2022. Offshore wind skills intelligence model report. https://aura-innovation.co.uk.
Pashakolaie, V.G., Heydari, K., Almena, A., 2023. Monetization of policy costs and sustainability benefits associated with renewable energy in fossil fuel-rich countries (FFRCs). Environ. Sustain. Indic., 100271
Price, R., Thornton, S., Nelson, S., 2007. The Social Cost of Carbon and the Shadow Price of Carbon: what They Are, and How to Use Them in Economic Appraisal in the UK.
Prisecaru, P., 2022. The War in Ukraine and the Overhaul of EU Energy Security, vol. 10. Glob. Econ. Obs.
Rojek, C., 2009. The labour of leisure: the culture of free time. labour Leis 1–216.
Rose, A., Wei, D., Einbinder, A., 2022. The co-benefits of California offshore wind electricity. Electr. J. 35, 107167.
Rutz, D., Janssen, R., 2014. Socio-economic Impacts of Bioenergy Production. Springer.
Sadorsky, P., 2021. Wind energy for sustainable development: driving factors and future outlook. J. Clean. Prod. 289, 125779.
Salvador, S., Ribeiro, M.C., 2023. Socio-economic, legal, and political context of offshore renewable energies. Wiley Interdiscip. Rev. Energy Environ. 12, e462.
Shao, J., Chen, H., Li, J., Liu, G., 2022. An evaluation of the consumer-funded renewable obligation scheme in the UK for wind power generation. Renew. Sustain. Energy Rev. 153, 111788.
Shields, M., Beiter, P., Nunemaker, J., Cooperman, A., Duffy, P., 2021. Impacts of turbine and plant upsizing on the levelized cost of energy for offshore wind. Appl. Energy 298, 117189.
Smart, G., 2016. Offshore wind cost reduction-recent and future trends in the UK and Europe. Offshore Renew. Energy Catapult. 1–10. Accessed 16 March 2020.
Sovacool, B.K., 2013. Energy policymaking in Denmark: implications for global energy security and sustainability. Energy Pol. 61, 829–839.
Sovacool, B.K., Mukherjee, I., 2011. Conceptualizing and measuring energy security: a synthesized approach. Energy 36, 5343–5355.
Swilling, M., 2020. The Age of Sustainability: Just Transitions in a Complex World. Taylor & Francis.
Tourkolias, C., Mirasgedis, S., 2011. Quantification and monetization of employment benefits associated with renewable energy technologies in Greece. Renew. Sustain. Energy Rev. 15, 2876–2886.
Tourkolias, C., Mirasgedis, S., Damigos, D., Diakoulaki, D., 2009. Employment benefits of electricity generation: a comparative assessment of lignite and natural gas power plants in Greece. Energy Pol. 37, 4155–4166.
Treasury, H.M., 2022. The Green Book: Central Government Guidance on Appraisal. Open Gov. Licence, London.
UK Government, 2023. Carbon Emission Factors and Calorific Values from the UK Greenhouse Gas Inventory (Ricardo Energy & Environment, 2022) to Support the UK ETS.
UNFCCC, 2009. Tool to Calculate the Emission Factor for an Electricity System-Version 7.0.
Woodman, B., Mitchell, C., 2011. Learning from experience? The development of the renewables obligation in England and Wales 2002–2010. Energy Pol. 39, 3914–3921.
World Bank, 2023. World Bank Commodity Price Data.
Xue, J., Gao, W., Guo, L., 2014. Informal employment and its effect on the income distribution in urban China. China Econ. Rev. 31, 84–93.
Yousuf, I., Ghumman, A.R., Hashmi, H.N., Kamal, M.A., 2014. Carbon emissions from power sector in Pakistan and opportunities to mitigate those. Renew. Sustain. Energy Rev. 34, 71–77.
Zhang, D., Rong, C., Ahmad, T., Xie, H., Zhu, H., Li, X., Wu, T., 2023. Review and outlook of global energy use under the impact of COVID-19. Eng. Reports 5, e12584.
Zhang, Q., Yang, K., Hu, Y., Jiao, J., Wang, S., 2023. Unveiling the impact of geopolitical conflict on oil prices: a case study of the Russia-Ukraine War and its channels. Energy Econ. 126, 106956.
Zhao, J., Dong, K., Dong, X., Shahbaz, M., 2022. How renewable energy alleviate energy poverty? A global analysis. Renew. Energy 186, 299–311.
Zhao, L., Yang, Y., Bai, X., Chen, L., Lu, A.-L., Zhang, X., Chen, W.-Q., 2023. Structure, robustness and supply risk in the global wind turbine trade network. Renew. Sustain. Energy Rev. 177, 113214.