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More than megawatts: The uneven socio-environmental returns from renewable electricity Contracts for Difference in the United Kingdom

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ABSTRACT

Economic analyses of renewable energy policy schemes typically focus on fiscal returns, deployment outcomes, and carbon savings, with broader socio-environmental impacts remaining under-researched. This study evaluates the United Kingdom's Contracts for Difference (CfD) scheme, assessing monetised social and environmental benefits for offshore wind, onshore wind, and solar photovoltaics (solar-PV) between 2016 and 2025. We develop a novel social cost–benefit framework combining avoided CO_2 emissions, estimated using UNFCCC marginal emissions methodologies, and employment-related social value, calculated using an opportunity-cost-of-labour approach. A technology-specific unemployment rate is introduced, weighting regional unemployment by the spatial distribution of renewable capacity to assess interactions with local labour markets. Substantial variation is observed between technologies. Cumulative discounted social and environmental impacts are estimated at £2.7 billion for offshore wind, £230 million for onshore wind, and £14 million for solar-PV. Relative to discounted CfD payments, socio-environmental returns are 0.35, 1.4, and 4.7 respectively. The returns improve across CfD Allocation Rounds (ARs): from 0.29 prior to AR1 to 5.8 in AR5, with an overall average of 0.45. Environmental benefits average £18-per-MWh and employment-related benefits £3.2-per-MWh. The technology-specific unemployment rates are 4.08% for offshore wind, 4.1% for onshore wind, and 3.92% for solar-PV. Monte Carlo analysis identifies carbon social value as the most influential factor, with a one percentage point change from £84-per-tCO_2 altering outputs by 1.3%. Overall, CfDs generate measurable positive socio-environmental impacts, though future CfD policy design should better integrate sustainability returns, domestic supply-chain development and regional skills development to support a just energy transition.

1. Introduction

Global renewable energy capacity is growing rapidly, driven by the political desire for climate action, advancements in technology efficiency and manufacturing capacity, increased investment, and supportive financial policies across the world. Renewable energy market expansion has led to significant reductions in the carbon intensity of electricity generation.

The UK Government aims to realise its climate change mitigation ambitions for the electricity sector by 2030 by supporting contracts for 50 GW of offshore wind, 35 GW onshore wind, and 50 GW of solar [1], with projections indicating offshore wind to account for over half of GB's electricity generation by 2030 [2]. Current progress indicates that greenhouse gas (CO_2) emissions per kWh electricity have reduced by 35% across the EU within a decade [3], and by 70% in the UK specifically (from 535 gCO_2/kWh to 162 gCO_2/kWh between 2008 and 2023). Further reduction in electricity-related emissions in the UK is planned through the seventh carbon budget by 2035, for an 88% reduction in electricity supply by 2040 [4]. Following COP29, the UK Government announced a revised target to achieve 81% total CO_2 emissions reduction by 2035, compared to 1990 levels [5]. Action towards greater renewable electricity generation aims to mitigate climate change and foster energy security and energy independence in the face of geopolitical shocks to global fossil fuel supply chains [6].

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The UK government has implemented a range of supportive financial policy mechanisms for renewable energy deployment, first through a system of Renewable Obligations Certificates (ROCs), which was discontinued for new applicants in 2017 and replaced by the Contracts-for-Difference (CfD) scheme [7]. The Energy Act 2013 established the legal framework for implementing the UK Government's Electricity Market Reform (EMR), aiming to secure electricity supply and decarbonise the electricity sector at a cost that remains affordable for consumers [8]. The first capacity through auction was awarded in 2015. The EMR framework introduced Contracts for Difference (CfDs) and a capacity market [9]. CfDs encourage investment in renewable energy by reducing the financial uncertainty associated with electricity market price fluctuation. This UK-specific policy transition is in line with the global uptake of CfDs as the primary policy tool used to support offshore wind [10]. CfDs are increasingly understood as a risk management and market creation tool rather than simply as subsidies. As Beiter et al. [11] argue, the CfDs transform volatile wholesale-market revenues into stable long-term price signals for renewable electricity investment; whereas Schlecht et al. [12] highlight potential dispatch and investment distortions and propose an evolutionary financial CfD design.

CfDs replaced the UK ROC scheme for long-term contracts between an electricity generator and Low Carbon Contracts Company (LCCC). CfDs enable the generator to stabilise its revenues at a pre-agreed level, called the strike price for the duration of the contract [13]. CfDs provide a two-way difference payment for electricity over a 15-year period (now 20 years in Allocation Round 7) between the market reference price and the strike price (indexed to $£_{2012}$, $£_{2024}$ for Round 7 onwards). The strike price is typically set through an auction, whereby the bidder offers the lowest strike price to win the CfD. Under the CfD scheme, 20 GW of contracts are recorded for offshore wind, of which 4.8 GW is fully operational (18 TWh/a) as of mid-2023, growing to 8.8 GW_e in 2024 (37 TWh/a), an additional 4 GW_e is under construction or commissioning. This is followed by 7.5 GW of solar-PV contracts with highest record of 3.3 GW in AR6. Furthermore, onshore wind's cumulative capacity amounted to 4.1 GW of contracts, with the most successful record in AR5 at 1.5 GW [14,15].

Past CfD auctions have seen the strike prices for offshore wind fall from $£_{2012}$120/MWh for power stations operational by 2017, to below $£_{2012}$40/MWh for power generation commencing operation in 2023/2024 [10]. The auction strike price for onshore wind and solar also declined by 48% and 30% between AR1 and AR4, respectively [14,16,17].

Each auction has a ceiling price, called the administrative strike price (ASP). The AR5 ASP set at £44/MWh did not take into account high inflation, rising capital costs, and ongoing post-Covid 19 supply chain constraints, with developers declaring projects to be financially unviable. Thus, AR5 failed to attract investors for offshore wind CfDs. AR6 and AR7 had more success due to the higher ASP, reflecting higher costs of production. The AR6 ASP for offshore wind at £58.87/MWh (for new projects) and £54.23/MWh (for previously successful projects), and AR7 ASP was £113/MWh for fixed-bottom offshore wind reflect this change [18,19].

Despite the CfD scheme's financial success in scaling renewable energy, the broader social and environmental impacts are important but under-researched components in measuring the relative success of the policy. These impacts include both positive benefits and negative costs experienced within broader society or the natural environment, that may not be reflected in the electricity market transaction, i.e. the positive and/or negative externalities, whereby costs and benefits spill-over to a third party not involved in the electricity sale [20]. Among the negative externalities, CO_2 emissions are critical, reflecting the climate change as a free-rider externality problem associated with fossil fuels, and underscores the importance of implementing carbon pricing to internalise the impact to the market price of electricity [21]. Among the positive externalities, job creation, continuing employment, education and skills development are key positive social development factors, as they lead to economic productivity and wage growth. Such factors are essential for achieving a *just transition* for workers living in fossil fuel employment-intensive regions as sectoral reform leads to the decline of fossil fuel demand. Renewable sector growth can thus counteract job losses, skilled workforce depletion and concomitant decline in social welfare from the decommissioning of fossil fuel systems [22].

At a national scale there are clear external social and environmental benefits that alleviate the so-called 'energy trilemma': including reducing the need for fossil-fuel-based energy imports leading to improvements in energy security [23–25], improving long term energy affordability by alleviating price shocks within volatile fossil fuel markets [26,27] and mitigating climate change [28]. Low carbon and renewable energy sources have contributed to job creation in the UK at an estimated 272,000 new roles by 2022 [29]. Some areas of job growth (such as the manufacturing capacity of domestic wind turbines) remain relatively modest, however [30]. Though growth in employment within the renewable energy sector is laudable at the national scale, job opportunities remain unevenly distributed geographically, particularly as low carbon transitions shift energy production sites from the coalfield heartlands towards predominantly rural and coastal locations [31]. Renewable energy transitions may thus act to reproduce existing patterns of regional social and environmental injustice experienced in so called 'left behind' places due to spatially inequitable land uses, historic planning policy, administrative fragmentation, and uncoordinated and spatially disoriented net zero policies [25,32,33]. Thus, understanding the spatial distribution of social and environmental benefits is a key aspect of ensuring a just CfD scheme for affected communities.

This study is structured around two main research objectives. First, it aims to assess the social and environmental impacts associated with electricity generation under the CfD scheme, with a specific focus on offshore wind, onshore wind, and solar photovoltaics (hereafter solar-PV) in the UK. Second, it seeks to compare these assessed impacts with the corresponding policy implementing costs, thereby enabling an evaluation of overall effectiveness of the CfD scheme. Analysis of offshore wind, onshore wind, and solar-PV contracts is drawn from publicly available data from the Low Carbon Contracts Company [34]. This twin objective analysis addresses three specific gaps in the literature. First, we integrate both monetised social and environmental aspects into CBA analysis for policy evaluation, eventually presenting a ratio to appraise energy policy. Second, though we tailored the model for CfD scheme analysis, our approach also provides a holistic cost-benefit evaluation approach suitable for application to a range of other energy policy instruments. Additionally, the model is designed to accommodate uncertainties, ensuring a robust and adaptable approach to energy policy evaluation. Third, our methodological innovation in employment impact assessment introduces a technology-specific unemployment rate to provide deeper insight into unemployment disparity in conjunction with renewable energy generation.

2. Literature review

Assessing the social and environmental impacts of renewable energy development can provide valuable insights, particularly when integrated within a comprehensive social cost benefit analysis (CBA) framework. Traditional CBA methodologies typically focus on explicit and realised costs and benefits, often overlook broader potential impacts [35–37]. Moreover, conventional CBA is primarily designed to assess investment viability and not sufficiently developed to evaluate the viability of policy interventions.

The scope and application of conventional CBA has undergone significant transformation, largely influenced by growing concern over rapidly deteriorating environmental conditions and future climate change threats [38,39]. Studies examining the use of environmental and social CBA analysis for various projects have therefore emphasised different pro-environmental outcomes and benefits. These include, but are not limited to quantification of ecological benefits, such as improved water quality or ecosystem restoration [40], changes to green finance and regulatory outcomes [41,42], changing uptake or practices of new renewables [43], or technological improvements in energy system modelling [44]. Multiple studies review the socio-environmental impact of renewable energy generation [45,46], including specific technology applications including offshore wind [47,48], biogas and bioeconomy adaptation [49,50], and solar-PV systems [51].

Despite this expanding project-level literature on social CBA analysis, comparatively, few studies have examined the social return of specific energy policy schemes. Research on the *social* impacts of electricity market support mechanisms highlights how consumer funded renewable support schemes shape distributional outcomes and sector level dynamics. Shao et al. [52] show that the renewable obligation in an earlier consumer funded schemes, generated substantial wind power deployment and lower price, but it was insufficient to offset the cost of renewable obligation scheme. Pashakolaie et al. [53] similarly showed that the social and environmental benefits are lower than the support scheme, while Nelson and Dodd [54] showed that the CfD mechanism is regressive form of taxation to fund renewable energy, leading to lower overall social equality. Thus, the social dynamics of electricity market support mechanisms show a variety of equity outcomes dependent upon the geographic and policy context in which they are applied.

Recent work also highlights wider market and financial effects of the UK CfD scheme. Chen et al. [55] show that supported wind generation can exert stronger downward pressure on wholesale electricity prices than non-supported wind generation, while Chen et al. [56] identify an enforcement gap associated with termination payments in offshore wind project-finance structures. These studies broaden understanding of CfDs as market design and financial risk instruments, but they do not quantify the scheme's monetised social and environmental returns.

Social CBA has been adopted as a decision-support tool by different government departments to evaluate policy outcomes, includes defining the scope of social and environmental costs and benefits, selecting the horizon of the impact, implementing country-specific discount rates [57,58]. In the UK, the Government's *Green Book* approach provides an extensive set of assumptions and methodologies for environmental and climate impact assessment [59]. Similarly, the Irish government issued similar guidelines, primarily focusing on climate impact assessment and the discounting of climate impacts. At a broader transnational governance level, the OECD contributed guidance for environmental CBA analysis, particularly emphasising climate-related concerns and the valuation of broader environmental damage. Despite these advancements, the incorporation of employment impacts within CBA framework remained underdeveloped [57]. Nevertheless, few studies have expanded the CBA scope to incorporate broader social and employment dimensions into project evaluation [60–62]. Several studies elaborated how to monetise the employment impact through the concept of opportunity cost of employment [63–65]. Social CBA itself has recently been developed to include job creation criteria given that employment effects are substantial drivers of social welfare [66]. This expanding literature signals a shift towards more comprehensive appraisal framework that integrates environmental, social and labour market impacts in energy policy evaluation.

3. Methods and materials

3.1. Socio-environmental return model

Our study introduces a social and environmental CBA framework to evaluate the societal outcomes of the CfD scheme in the UK. The framework evaluates both the policy cost and associated impacts. The policy cost refers to the CfD payments (expenditures) by the UK government. The social and environmental impacts are built upon two key sustainability aspects of renewable energy development including CO_2 emissions reduction and employment. The CBA framework is structured to measure the discounted social and environmental impacts and associated *CfD* payments as follows:

$$CfD\_socio\_environmental\ return = \frac{PV\left(Env_{sim/fle,t,i}\right) + PV\left(Soc_{t,i}\right)}{PV\left(CfD_{t,i}\right)} \quad (1)$$

The variable *CfD_socio_environmental return* represents the social and environmental return, which is calculated as the present value of total benefits relative to the total payments. This ratio particularly indicates the proportion of CfD scheme payments that could be offset by social and environmental benefits of renewable energy.

To evaluate greenhouse gas emissions reduction (specifically CO_2), this study adopts the United Nations Framework Convention on Climate Change (UNFCCC) methodology. This framework distinguishes between two scenarios: a *simple scenario* (aligned to option A in UNFCCC) and a *flexible scenario* (aligned to option B) [67].

In this context, $PV\left(Env_{sim/fle,t,i}\right)$ represents the present value of environmental impact in simple and flexible (*sim*/*fle*) scenarios for renewable technologies (t). $PV\left(Soc_{t,i}\right)$ stands for present value of employment value. $CfD_{t,i}$ indicated the CfD payment associated with each renewable energy technology. In addition, "the opportunity cost of labour" approach is used to assess the employment impact [63].

The study process began with data collection and analysis of CfD scheme payments for solar-PV, offshore wind, and onshore wind from 2016 to 2025. The UNFCCC methodology was used to measure fossil fuel substitution, serving as an intermediate variable for assessing environmental impact. It is followed by employment impact assessment and final computation of the CfD scheme socio-environmental return. To account for uncertainty, a sensitivity analysis was performed using a Monte-Carlo simulation (Fig. 1).

3.2. CfD scheme

Under the CfD, contract strike prices remain fixed for the duration, though they are adjusted annually to account for inflation and market-related charges [68]. Since the CfD scheme introduction, seven allocation rounds have been completed. These allocation rounds have supported a cumulative installed capacity of 43.1 GW_e [15]. Offshore wind dominates this capacity with 24.8 GW_e, followed by solar-PV with 7.5 GW_e and onshore wind with 4.1 GW_e under CfDs. Electricity generation from offshore wind has also grown significantly: increasing from 1.5 TWh in 2017 to 13.6 TWh in 2024. Onshore wind generation rose from 44 GWh in 2018 to 1 TWh in 2024, while solar-PV shows a more gradual upward trend, from 6 GWh in 2016 to 19 GWh in 2024 (Fig. 2).

Payments from the CfD scheme across the three technologies and allocation rounds are shown in Table 1. This table shows the breakdown of annual payments made under the CfDs from Pre-AR1 (Investment contracts) to AR5 [34]. There is significant year-to-year variation, driven by fluctuation in the market reference prices, change in generation capacities, and differences in payment settlement dates.

It is important to note that while CfD payments are negative in certain years, the cumulative payment over the full period remains positive in all cases except for solar-PV under AR4/AR5 in 2025, where the CfD payment is the only payment observed to be negative. Solar-PV under AR4 contains £1.2 mn positive payments and £−2.03 mn negative payments, whereas AR5 breakdown consists of £0.02 mn positive, and £−0.03 mn of negative payments. To address the negative payments for solar-PV in AR4/AR5, two approaches were applied. In the first approach negative payments were excluded from the socio-economic return calculation of solar-PV under AR4/AR5, and in the second approach, negative payments were treated as positive *non-social* benefit and added to the benefit side of the model.

3.3. Environmental impact assessment

Environmental impact is quantified in this study as the discounted

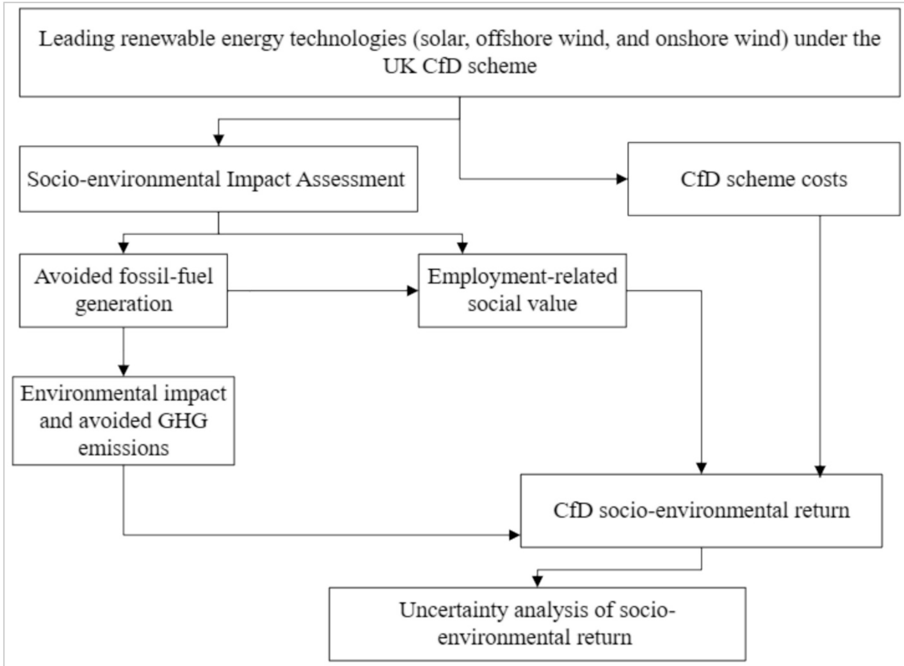

Fig. 1. Conceptual and analytical framework for estimating the socio-environmental return of renewable electricity generation under the CfD scheme.

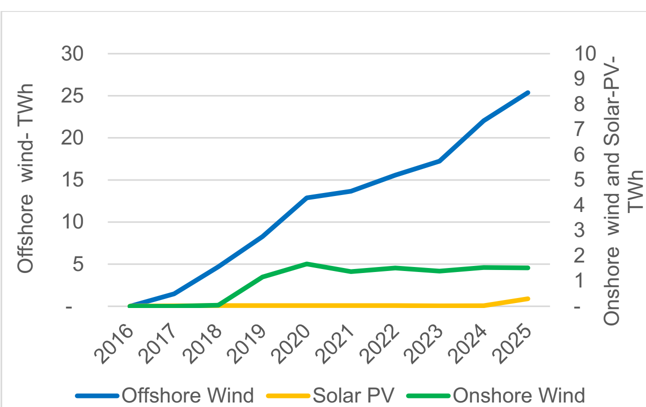

Fig. 2. Annual electricity generation from offshore wind, onshore wind, solar-PV supported under United Kingdom Contracts for Difference scheme between 2016 and 2025 (TWh).

value of CO_2 emission reduction through renewable energy generation as follows [69,70]:

$$PV\left(Env_{sim/fle,t,i}\right) = \sum_{i=2016}^{2025} \frac{EF_{c-(sim/fle)}{}^{*}G_{t,i}{}^{*}cv_i}{(1+d)^t} \quad (2)$$

The variable $PV\left(Env_{sim/fle,t,i}\right)$ represents the present value of total environmental impact in year i for either simple or flexible scenarios, (in £mn). The term d signifies the social discount rate, with all values discounted to the base year 2016. For this analysis, the Social Rate of Time Preference (STP) of 3.5% has been applied for social discount rate [59,71]. $G_{t,i}$, stands for electricity generation (TWh) of technology (t) over time (y).

$EF_{c-(sim/fle)}$ represents the marginal emissions factor (t_{CO2}/MWh). Based upon the UNFCCC framework, the marginal emissions factor calculates the potential displacement of either existing or forthcoming fossil fuel power stations (natural gas, oil, and coal) by renewable energy sources. Displacement can occur across all existing fossil-fuel powered capacity whether operating as baseload generation or not, as well as the most recent non-renewable energy generation capacity additions. To capture these effects, the framework incorporates three key components: Operating Margin (OM), Build Margin (BM), and Combined Margin (CM) [67]. OM refers to the emissions from existing power stations under the simple and flexible scenarios. In the simple scenario, all current power generation capacity is considered, excluding low-cost/must-run power stations (assumed here as nuclear or hydro power). Conversely, the flexible scenario includes all existing power generation sources. The BM reflects the CO_2 emissions from the most recently added non-renewable energy capacity. Recent power station construction in the UK including the Carrington Power Station commissioned in 2016 [72], and Keadby 2 Power Station operational since in February 2023 [73] are key examples. We use the emissions factor of gas-fired power stations (i.e. combined cycle gas turbine - CCGT) to represent the BM [71,72,74,75]. The OM margin emissions factor is calculated as the weighted average CO_2 emissions per MWh, using the following formula:

$$EF_{M,ft,i} = \sum_{i=2016}^{2025} \frac{EG_{ft,i}.EF_{ft,i}}{\sum EG_{ft,i}} \quad (3)$$

$EF_{M,ft,i}$ represents marginal emissions factor of fossil fuel technologies (ft) measured in t_{CO2}/MWh. The term $EF_{ft,i}$ refers to the emissions factor associated with specific fossil fuel technologies. These factors correspond to the primary fossil fuel sources used for electricity generation including: natural gas, oil, and coal, with emission intensities of 186 kg_{CO2}/MWh, 285 kg_{CO2}/MWh, and 336 kg_{CO2}/MWh, respectively [76]. The variable $EG_{ft,i}$ represents the net electricity generation from fossil fuel technologies in year i (MWh). The proportion of $EG_{ft,i}$ relative to the total generation from all fossil fuel sources indicates the share of each technology in overall fossil-based electricity generation. The CM factor is calculated as the weighted average of 'simple' and flexible OM, along with the BM factor, as follows:

$$EF_{c-sim} = (1 - M_d)^*(0.25^*EF_{o-sim} + 0.75^*EF_b) \quad (4)$$

$$EF_{c-fle} = (1 - M_d)^*\left(0.25^*EF_{o-fle} + 0.75^*EF_b\right) \quad (5)$$

EF_{c-sim} and EF_{c-fle} represent the CM emissions factors for the simple and the flexible scenarios. EF_{o-sim}, and EF_{o-fle} denotes the emissions factor for simple, and flexible OM factor, and EF_b represents the BM

Table 1
Annual CfD payment settlements (£mn) for solar-PV, offshore wind, and onshore wind across CfD allocation rounds (Pre-AR1 to AR5), showing interannual variability driven by market prices and generation levels.

ARs	Renewable technologies	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Pre-AR1	Offshore	0.0	166	471.2	915	1252	478	8.6	897	1147	1118
	Onshore	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Solar-PV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AR1	Offshore	0.0	0.0	0.0	9.7	186	65.8	−70	165	175	288.5
	Onshore	0.0	0.0	1.3	55	89	−18.7	−95.3	18.0	56	49.4
	Solar-PV	0.3	0.7	0.8	1.2	1.5	−0.2	−2.6	0.2	0.8	1.0
AR2	Offshore	0.0	0.0	0.0	0.0	0.0	−28.0	−80.3	24.6	112	76.2
	Onshore	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Solar-PV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AR4	Offshore	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Onshore	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Solar-PV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.8
AR5	Offshore	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Onshore	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Solar-PV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.01
Total	Offshore	0.0	166	471	925	1438	516	−141	1086	1433	1482
	Onshore	0.0	0.0	1.3	55	88.5	−18.7	−95.3	18.0	56	49.4
	Solar-PV	0.3	0.7	0.8	1.2	1.5	−0.2	−2.6	0.2	0.8	0.1

emissions factor. In line with UNFCCC figures [67], the operating and build margins of wind and solar-PV projects are weighted at 0.75, and 0.25, respectively.

M_D represents the daily marginal CO_2 reduction factor which captures the impact of variable output from renewable energy sources. This factor differentiates the relative contribution of solar-PV and wind to CO_2 reduction. Due to the intermittent nature of most renewable energy sources, fossil fuel-based power stations may be required to operate in a more dynamic operating mode to balance the grid stability. Jansen et al. [77] suggest that the marginal CO_2 emissions reduction could be offset by approximately 8.3% and 4.9% for solar-PV and wind, respectively.

To present the monetary value of CO_2 emissions reduction, this study adopts an average carbon social value (cv_i) of 84.2£/$t_{CO2,}$ for whole study period based on the average of most recent carbon social values reported by the UK government sources. While some reports span the full study period, others cover only specific years (Table 2). Among these reports, the UK Emissions Trading Scheme (ETS) – a cap-and-trade scheme – came into effect on 1st January 2021 and provided the data for carbon pricing from 2021 to 2023 [78,79].

The Green Book carbon value is used for the years 2020–2024 [80] and Department for Energy Security and Net Zero (DESNZ) provide four different scenarios including market carbon values, a low sensitivity scenario (defined as high fossil fuel prices and low economic growth), a net zero strategy aligned scenario, and a high sensitivity scenario (defined as low fossil fuel prices and high economic growth).

3.4. Social impact assessment

Employment-related social impact refers to the measurable benefits derived from job creation. Employment delivers a wide range of advantages to individuals, families, and society. However, employee wages represent an opportunity cost, and so *wage* serves as a primary indicator for assessing these benefits [83]. The opportunity cost of labour is primarily influenced by the unemployment rate. When unemployment is high, it is more likely that a newly employed worker was previously unemployed, thereby generating greater social value through employment. Conversely, a low unemployment rate reduces the likelihood of hiring someone who is currently unemployed.

Employment also provides additional social wellbeing benefits, particularly related to mental and physical health, and consequent reduction in mortality and morbidity risks [84–86]. Unemployment has a statistically and economically significant effect on the incidence of burglary, auto theft, and drug possession, thus enhanced employment has concurrent individual and collective social benefits such as: lower rates of violent and non-violent crime, substance dependency and anti-social behaviour [87,88]. However, these indirect social impacts are not yet fully captured within existing social value assessment frameworks. To account for these quantifiable variables, we developed the following equation [34,89]:

$$PV\left(Soc_{t,i}\right) = \sum_{i=2016}^{2025} \frac{Em_{t,i}{}^{*}G_{t,i}}{(1+d)^{t}} \tag{6}$$

$PV\left(Soc_{t,i}\right)$ stands for the discounted value of total employment social impact (£mn), $Em_{t,i}$ represents the total employment-induced social impact, measured as follows:

$$\begin{aligned} Em_{t,i} = {} & \left(EF_t - EF_g\right)^{*}EF_m{}^{*}C_{t,i}{}^{*}\left[P\left(U_{w,i}\right)^{*}\left(W_{t,i} - I_0 - L\right)\right. \\ & \left. + \left(1 - P\left(U_{w,i}\right)\right)^{*}\left(W_{t,i} - W_0\right)\right] \end{aligned} \tag{7}$$

The variable $Em_{t,i}$ represents the value of employment impact in £mn, $\left(EF_t - EF_g\right)$ captures the net employment impact Full-time Equivalent (FTE/MW), calculated by subtracting the employment factor of a natural gas power station (EF_g) from that of equivalent renewable energy technologies (EF_t). According to [90], offshore, onshore wind, and solar-PV employment during construction or operation presented average of 0.94, 0.58, and 0.75 FTE/MW in the UK from 2014 to 2020,

Table 2
Carbon social values (£/t_{CO2}) applied in the environmental impact assessment, compiled from UK government sources and market-based carbon pricing schemes.

Reports	2016	2017	2018	2019	2020	2021	2022	2023	2024	Ref
Thrust	28.7	29.1	29.4	29.8	30.1	30.4	30.8	31.1	31.5	[81]
Policy report					40	42.7	45.3	48	50.7	[82]
UK ETS carbon price		–	–	–	–	48.0	52.6	83	–	[78]
Green book	–	–	–	–	253	257	261	265	269	[59]
Market carbon value	–	–	–	–	–	–	–	70	72	
High sensitivity	–	–	–	–	–	–	–	51	63	
Net zero strategy	–	–	–	–	–	–	–	59	76	[80]
Low sensitivity	–	–	–	–	–	–	–	64	84	

respectively. EF_g value is considered 0.3 in the model [91].

$C_{t,i}$ signifies renewable technologies capacity (GW). EF_m represents employment multiplier factor accounts for indirect and induced job creation. From UK ONS data [90], we find that employment multiplier of solar-PV in the UK fluctuated around 2.08, offshore wind varied from 1.8 to 2.4, and onshore wind varied from 2.4 to 2,7 from 2016 to 2020, with average multiplier of 2.08, 2.08, and 2.53 for solar-PV, offshore, and onshore wind, respectively. This average is used for the period 2021 to 2025.

The variable $P(U_{w,i})$ represents the probability (P-value) that a newly employed worker was previously unemployed. Conversely, $(1 - P(U_{w,i}))$ reflects the likelihood an individual was already employed. This probability is a function of the prevailing unemployment rate [64,92]. However, to enhance the precision of this estimation, we extended the conventional unemployment rate by incorporating a novel approach that we term the *technology-specific unemployment rate* ($U_{w,i}$). This approach captures regional disparities in unemployment and the distribution of renewable technologies and finally evaluate the P-value using unemployment rate distribution curve proposed by Haveman and Krutilla [92]. The details are covered in the subsequent Section 3.4.1.

The variables $W_{t,i}$ and W_0 represent the wages of employees in the new and previous jobs respectively. W_0 assumed as 80% of $W_{t,i}$. I_0 denotes the potential income of a new worker that was previously unemployed. This is assumed to be 20% of $W_{t,i}$, L represents the value of leisure as an opportunity cost, and is considered to be 20% of $W_{t,i}$ [69].

To estimate $WG_{t,i}$ the average wage for key occupations within each renewable energy technology was applied. For solar-PV, the estimated average wage of three main occupations including solar-PV design engineer, solar-PV installer, and solar-PV electrician is estimated as £33.5 k/year. Offshore wind salaries were based on an average of £38.5 k/year, derived from three primary occupations: wind turbine technician, offshore drilling worker, and marine engineer. For onshore wind, an average wage of £36.5 k/year is applied, derived from average wage of turbine technician, wind developer, and electrical technician [93,94]. All wage estimates are presented in nominal terms, assuming that wage growth offsets the effect of discounting.

3.4.1. Technology-specific unemployment rate

The variation in spatial distribution of renewable energy installation has concomitant effects upon regional employment/unemployment rates. To capture the effect of the regional unemployment rate on renewable energy social impact, our novel *technology-specific unemployment rate function* reflects the premise that renewable energy development in regions with higher unemployment rate could generate greater social benefits, as newly employed workers are more likely to have been previously unemployed. The technology-specific unemployment rate is calculated as follows:

$$U_{w,i} = \sum_{i=2016}^{2025} \frac{U_{r,i}.C_{t,i}}{\sum C_{t,i}} \tag{8}$$

The variable $U_{w,i}$ represent the technology-specific unemployment rate across the three renewable energy technologies studied, calculated using the weighted average unemployment rate in across a differentiated renewable energy distribution map. $U_{r,i}$ refers to the regional unemployment rate, and $C_{t,i}$ signifies renewable energy capacity across different regions. This accounts for how renewable energy generation capacity is distributed unevenly across UK regional geography due to a combination of varying geographic characteristics (including natural geographic features such as coastal access and solar-PV irradiance), access and proximity to centralised grid infrastructure, spatial targeting of economic development policy (including but not limited to political devolution and the development of regional industrial clusters) [95], and levels of social opposition (notably to onshore wind farms and solar-PV farms) [96,97].

Although the technology-specific unemployment rate metric helps to distinguish and quantify the regional unemployment disparity, it operates under two assumptions. First, is the assumption that all regions have similar levels of skilled labour, though in practice skill types vary regionally due to prevailing industry trends, historical differences, and other social and economic factors [98]. Second, is that the labour market draws upon a local personnel base, though in reality it draws from a mixture of local, national, and international worker networks which we cannot account for in the model.

Analysis of the regional distribution of renewable energy capacity ($C_{t,i}$) in the UK reveals that offshore wind is predominantly concentrated in the North East and North West of England, which together accounted for nearly 50% of the total installed capacity between 2016 and 2023. While the South-East has seen a relative decline in offshore wind, other regions have experienced growth, notably, the Yorkshire and Humber region has shown an upward trend driven by the Dogger Bank project [99]. Yorkshire and Humber's strategic coastal location positioned it as a hub for new offshore developments aimed at supplying electricity to industrial operations and future hydrogen production linked to the Tees Valley industrial cluster. Additionally, Scotland has emerged as a key player in offshore wind energy, leveraging its abundant resources to drive substantial growth and employment.

In the onshore wind sector, Scotland contributes approximately 60% of the UK's total installed capacity. Therefore, any employment social value model for renewable energy development at the UK-scale should significantly emphasise Scotland's employment figures to accurately capture the economic and social dynamics within the Devolved Administration.

Solar-PV is most prominent in the South-West, South-East, and East of England. The South-West leads with nearly 30% of the UK's total installed capacity, followed by the South-East at around 25%. The East of England and East Midlands also contribute significantly to the overall solar-PV capacity. Collectively, these four regions constitute approximately 70% of the total solar-PV installed capacity (Fig. 3).

Fig. 4 shows that the regional employment rate ($U_{r,i}$) range from 4% to 6% across all regions during the period 2016–2024, showing a downward trend with a noticeable spike in 2021, driven by the effect of the COVID-19 pandemic. Among all regions, North-East England shows a slightly higher unemployment rate than the national average, reflecting persistent social and economic challenges linked to the structural unemployment experienced in a post-industrial economic and political landscape [100], and the subsequent revitalisation of high value manufacturing sectors within successive economic development policies and the emerging industrial cluster [101,102]. In contrast, Northern Ireland is recognised for its potential in onshore wind development, and demonstrates consistently lower unemployment rates, indicating greater economic resilience and potential for stable employment opportunities.

4. Results

4.1. Environmental (emission reduction) impact

The emissions reduction factor results, which represent the most critical variable for environmental impact assessment, are shown in Table 3. The findings show that emissions reduction factors are variable and declining over the study period. It also shows that offshore and onshore wind are slightly greater than solar-PV due to inclusion of the output intermittency factor (M_d) in the emissions factor assessment. The average emissions factors for solar-PV are 0.25 and 0.22 in simple and flexible scenarios, respectively. The emissions factor amounted to 0.26 in simple and 0.23 flexible scenario of offshore and onshore wind energy. As anticipated, the emissions factor for the simple scenario is higher than the flexible one. The emissions factors show a downward trend, primarily due to efficiency improvements within fossil fuel-based power stations. Such advancement reduces fossil fuel consumption overall and subsequently enhances the CO_2 emissions factor.

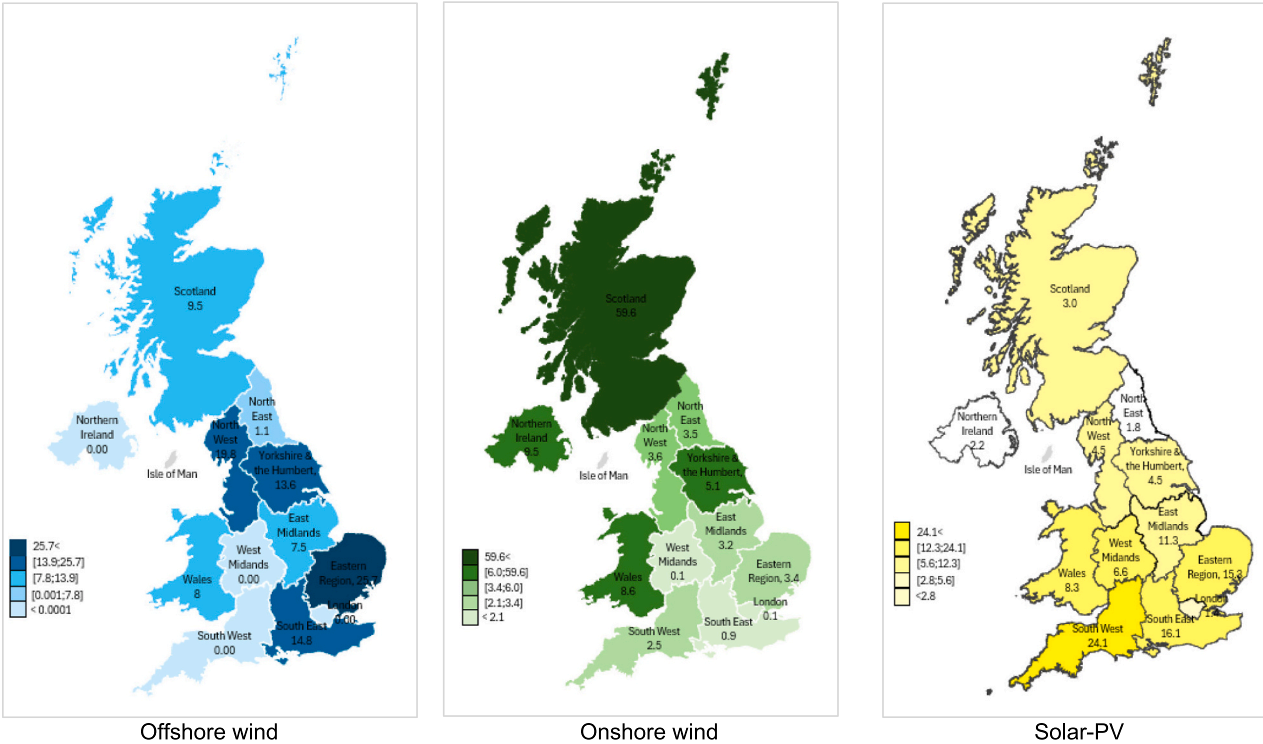

Fig. 3. Spatial distribution of installed capacity for offshore wind, onshore wind, solar-PV across UK regions, illustrating regional concentration patterns relevant to employment social impact [76].

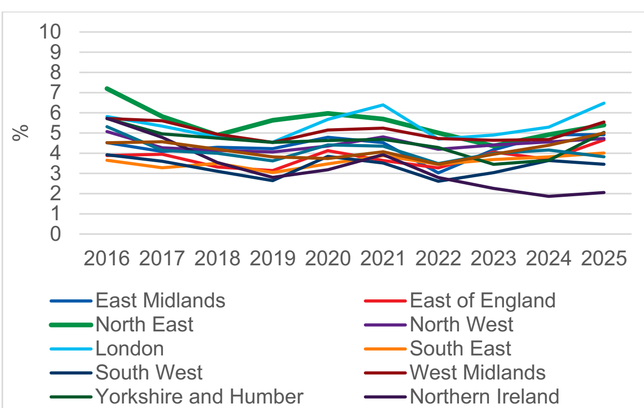

Fig. 4. Regional unemployment rates across the UK from 2016 to 2025, highlighting inter-regional variation relevant for technology-specific unemployment rate [80].

As illustrated in Fig. 5, offshore wind development is associated with a substantial CO_2 reduction impact. The cumulative discounted environmental impact of offshore wind is estimated at £2.3 billion (bn) in the simple scenario, and £2.1 bn in the flexible scenario. The impact increased nearly eleven-fold from £38 mn in 2017 to £418 mn in 2025 in the simple scenario, reflecting a rapid increase in offshore electricity

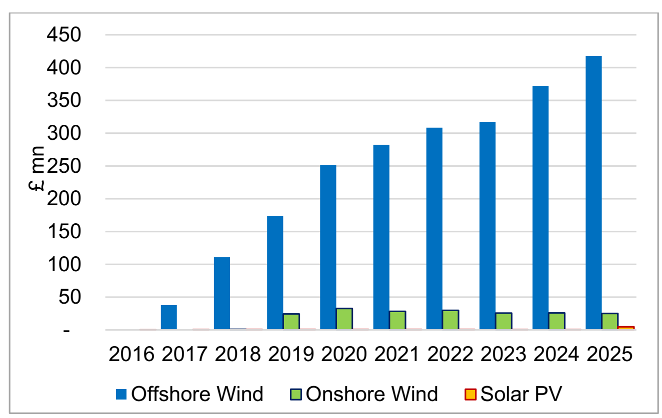

Fig. 5. Discounted monetary value of CO_2 emission reductions (£ mn, 2016 prices) - attributed to renewable electricity generation under the CfD scheme, computed using the UNFCCC simple scenario.

Table 3
Estimated marginal CO_2 emission reduction factors (tCO_2/MWh) for wind and solar-PV technologies under simple and flexible UNFCCC emission displacement scenarios, 2016–2025.

Renewable technologies	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Offshore/onshore wind										
EF_{c-sim}	0.33	0.30	0.28	0.25	0.23	0.25	0.23	0.22	0.21	0.19
EF_{c-fle}	0.27	0.25	0.24	0.22	0.21	0.22	0.21	0.20	0.19	0.18
Solar-PV										
EF_{c-sim}	0.32	0.29	0.27	0.24	0.22	0.24	0.23	0.21	0.20	0.19
EF_{c-fle}	0.26	0.24	0.23	0.21	0.20	0.21	0.20	0.19	0.19	0.17

generation from 1.5 TWh in 2017 to 25.4 TWh in 2025.

By contrast, for onshore wind, total environmental impacts in the simple and flexible scenarios were £193 mn and £173 mn respectively, rising from £1 mn in 2018 to £25 mn in 2025. Solar-PV technology represents the smallest total environmental impact across all technologies due to lower generation capacity, cumulating to £9 mn in the simple scenario, growing from £0.17 mn 2016 to £4.7 mn in 2025.

4.2. Social and employment impact

As shown in Fig. 6, technology-specific unemployment rates across all renewable energy technologies follow a broadly similar trend. However, onshore wind shows the highest unemployment rate, suggesting of higher social value for new workers. This trend highlights the finding that offshore and onshore wind development has been concentrated primarily in northern regions of the UK, where unemployment rates are demonstrably higher than the UK average. By contrast, the technology-specific unemployment rate for solar-PV is lowest, reflecting its predominance in the southern regions of the country, where unemployment rates are typically lower and per capita income is correspondingly higher.

The technology-specific unemployment rates are estimated at 3.92% for solar-PV, 4.08% for offshore, and 4.1% for onshore wind (Fig. 6). These values were integrated into the distribution curve framework proposed by [92]. Consequently, the model assigned P-values of 0.9% for solar-PV, 1.1% for offshore wind, and 1.3% for onshore wind.

Fig. 7 shows the discounted social value across all technologies. Although it is primarily driven by electricity generation, it is also influenced by a range of technical and economic factors, including direct and indirect employment factors, the gas power station employment factor, wages, and the discount rate.

Results show that discounted social value of offshore wind increased from £5.3 mn in 2017 to £99 mn in 2025, resulting from rising electricity generation under the CfD scheme. Onshore wind delivered the next largest discounted social value by total of £37 mn, increased from £0.2 mn in 2018 to £5.6 mn in 2025, an increase by a factor of 37, tied to a 35× surge in onshore electricity generation. For comparison the onshore wind social impact growth is larger than its environmental impact (×25), due to a gradual decline in the marginal emissions reduction factors. The social value of solar-PV also rises from £0.06 mn in 2016 to £0.25 mn in 2024, and £3.06 mn in 2025.

4.3. CfD socio-environmental return

Before examining the CfD scheme's socio-environmental return, the environmental and social impact results are normalised per MWh to provide deeper comparison of the impact across three technologies (Fig. 8).

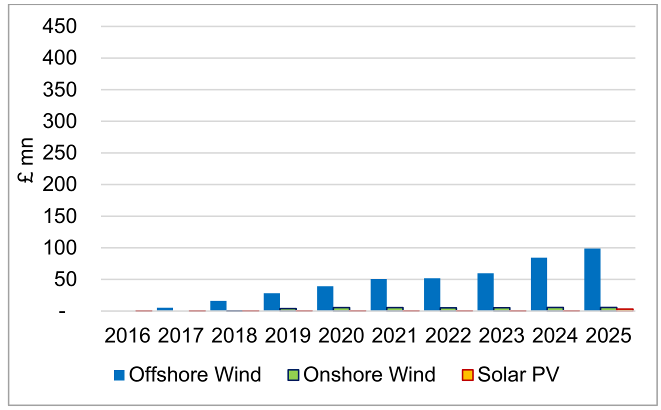

Fig. 7. Discounted employment related social impact (£ mn, 2016 prices) - generated by renewable electricity technologies supported under the CfD scheme, estimated using the opportunity cost of labour approach simple scenario.

Environmental impacts per MWh show a similar pattern across all three technologies. In the simple scenario, offshore wind delivers £18/MWh, onshore wind £16/MWh, and solar-PV £20/MWh. These differences are attributed to variation in the M_D factor (Eqs. (4), (5)), and to differences in electricity generation profiles across technologies. In addition, under the flexible scenario, the impacts drop by £2/MWh across all technologies.

In contrast, social impact shows wider variation, while solar-PV social impact averages £9.2/MWh, offshore wind and onshore wind average £3.2/MWh and £2.8/MWh, respectively. The higher social value of solar-PV stems from the interaction of three main components of the model: load factors, unemployment rates, and wage scales. Regarding the load factor, solar-PV shows an average of 11% during 2016 to 2023, compared to 40% for offshore wind, and 26% for onshore wind [103]. However, solar-PV development is also associated with lower regional wages and slightly lower unemployment rates. This implies that the influence of the load factor outweighs the effects of wages and the unemployment rate on the overall social value.

Finally, the total offshore impact amounted £21.3/MWh in the simple, and £19.2/MWh in the flexible scenario, and £18.5/MWh, and £16.5/MWh in the simple and the flexible scenarios of onshore wind, respectively. For solar-PV the simple and the flexible scenarios also present £29.4/MWh, and £27/MWh, respectively.

Fig. 9 compares the socio-environmental return across all

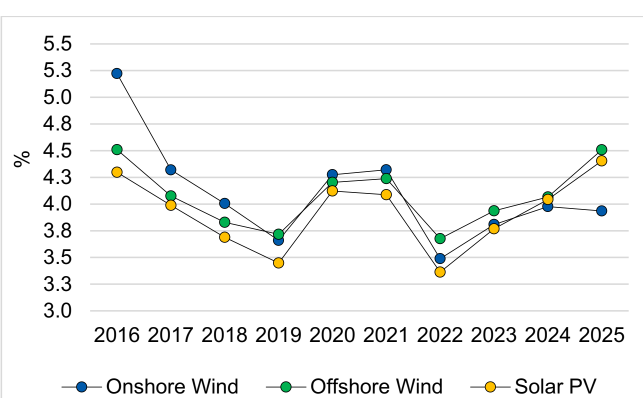

Fig. 6. Technology-specific unemployment rate for offshore wind, onshore wind, solar-PV -, derived by weighting regional unemployment rates by the spatial distribution of installed renewable capacity.

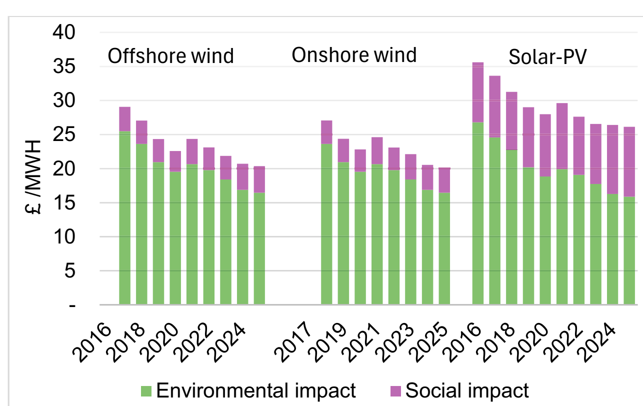

Fig. 8. Environmental and social impacts normalised per unit of electricity generation (£/MWh) for offshore wind, onshore wind, solar-PV under the CfD scheme, based on the simple emission reduction scenario.

technologies. Results show that despite the UK's comparatively higher geographic potential for offshore wind relative to solar-PV, solar-PV delivers the highest socio-environmental return, and offshore wind ranked as the lowest. We attribute the primary driver of this disparity to the CfD scheme payment, as solar-PV CfD averages at £32/MWh versus £83/MWh, and £35/MWh for offshore and onshore wind, respectively.

Solar-PV records 4.8 in the simple scenario and 4.5 in the flexible scenario, giving an average of 4.7. This exceptionally high return is attributed to 2025, specifically, associated with a low strike price and high electricity generation performance. To highlight the significance of 2025 in the solar-PV socio-environmental assessment, we temporarily excluded it from the dataset with the results indicating a substantial reduction in return – falling to 1.7 over the 2016–24 period. The onshore wind average socio-environmental return amounted to 1.49 in the simple scenario and 1.36 in the flexible scenario, while offshore wind presented 0.37 in the simple scenario and 0.34 in the flexible scenario.

The breakdown of the CfD scheme returns according to Allocation Rounds (AR) is presented in Fig. 10. The overall trend of socio-environmental return is increasing, particularly with regards to solar-PV. The return of solar-PV in AR4/AR5 is above 5.0 while it was below 1.0 in AR1. This disparity primarily stems from the strike price averaged at £96/MWh in AR1 and £66/MWh in AR4 and AR5. This made the CfD scheme payments 7.8 times cheaper per MWh of solar-PV generation in AR4 and AR5 (£3.7/MWh) compared to AR1 (£29/MWh).

Table 1 shows where the positive CfD scheme units are applied in solar-PV projects in AR4/AR5, to address the issue of negative payments. While this approach addressed the issue, it compromises the solar-PV in the AR4/AR5 return. Alternatively, in the second approach, the negative CfD units are treated as positive *non-social* benefits. Our findings indicate that adopting this approach can raise the return to 7.4, including 1.7 of *non-social* benefits.

The socio-environmental return gap between AR1 with AR4/AR5 is smaller than the corresponding payments per MWh gap. This difference in socio-environmental return is due to the slightly higher socio-economic performance of AR1 compared to AR4/AR5, driven by progressive grid decarbonisation, and a declining CO_2 emissions factor (Table 2).

For solar-PV generation, all Allocation Rounds deliver a broadly similar social value of £8/MW. However, in term of the environmental value of solar-PV and other technologies, this study assumes a fixed CO_2 social value over the entire study period. The social cost of CO_2 is expected to follow a rising trend in the future as the likelihood and severity of climate change impacts from extreme weather events, biodiversity loss, and sea level rise increase. Therefore, newer ARs may lead to higher environmental impacts than older ones if the social value of CO_2 grows faster than grid decarbonisation efforts.

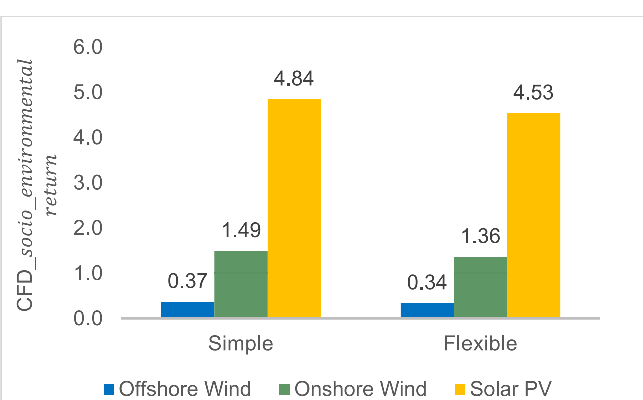

Fig. 9. Social-environmental return ratios for renewable energy electricity technologies supported by the UK CfD scheme, expressed as the ratio of discounted social and environmental benefits to discounted CfD policy payments.

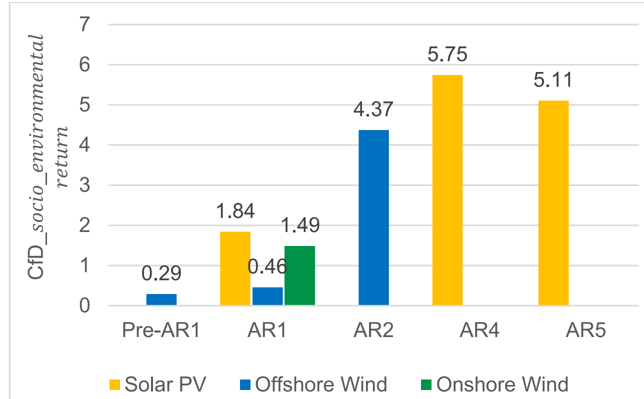

Fig. 10. Socio-environmental return of renewable electricity generation under successive CfD allocation rounds (Pre-AR1 to AR5), illustrating changes in policy effectiveness over time.

Focusing on offshore wind, the socio-environmental return increases markedly from 0.29 pre-AR1 to 0.46 in AR1 and 4.4 in AR2. This due primarily to substantial declines in the strike price from an average of £153/MWh in AR1 to £90/MWh in AR2. This strike price disparity led to an average CfD payment per MWh of £57/MWh in AR1, accompanied by environmental benefits of £14.5/MWh, and a social benefit of £2.8/MWh. By contrast, the CfD payments in AR2 amounted at £12.8/MWh, with an environmental impact of £14/MWh and a social impact of £3/MWh.

These findings underscore the importance of the strike price and CO_2 emissions factors in CfD allocation. Moreover, as real wages in the UK economy have increased only marginally, thus the social value of employment remains relatively unchanged. To enhance the social benefits of CfDs over time, improvements in employment-related factors would need to accompany future allocation rounds.

To evaluate the effect of input uncertainties on the CfD socio-environmental return, a Monte-Carlo simulation was performed using the MS Excel Plugin (@Risk-Decision Tools Suite 8.3.0). The Pert distribution function was applied, incorporating ±20% variation in the model parameters. The model was initially run with 5000 iterations, and to ensure the uncertainty is comprehensively captured, a further 10,000 iterations were completed.

Fig. 11 presents a tornado plot laying out how each input causes variation in the offshore wind socio-environmental return. CO_2 social value emerges as the most influential factor. A ±20% fluctuation changes the return from 0.31 to 0.39, highlighting the critical role of carbon pricing in shaping social outcomes. The wage of employees

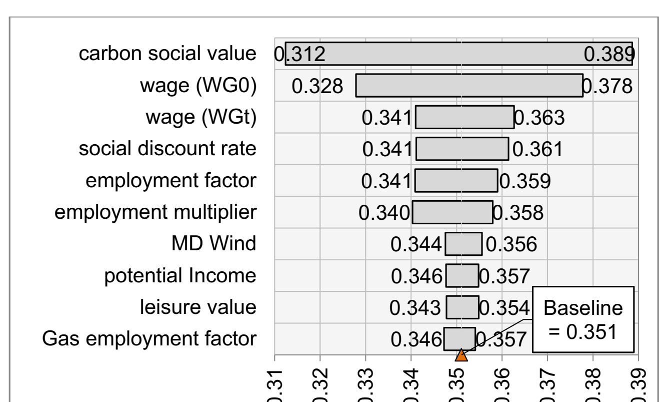

Fig. 11. Tornado plot showing the relative influence of key economic, environmental, and employment parameters on the socio-environmental return of offshore wind generation.

stands as the second and third-most important influential factors, generating variation from 0.32 to 0.38. The social discount rate comes next, changing the socio-environmental return from 0.34 to 0.36.

The CO_2 social value is the most influential driver of return variation for onshore wind, inducing a 24% fluctuation (from 1.275 to 1.572) in response to a ±20% change in CO_2 social value. Return fluctuation for onshore and offshore wind are identical and substantially higher than solar-PV (18%), due to higher share of environmental impact within the total impact for offshore wind (85%) compared to solar-PV (65%), as shown in Fig. 8. The sensitivity of onshore wind socio-environmental return to a ±20% change in wage is comparable to that offshore wind, resulting in a 15% variation. The social discount rate stands out as the next most influential factor, generating 5% variation in return, followed by changes in other employment assumptions, which generates a negligible effect on returns (Fig. 12).

The tornado plot of the solar-PV socio-environmental return demonstrates that ±20% change in the previous wage (WG_0) contributes the highest changes in return by 33%. This is attributed to the higher share of the employment impact in the solar-PV return. The second most influential factor is the CO_2 social value. Its variation by ±20% creates a 18% variation in return. This is followed by variation in current wage. A 20% increase in wage raises the return by 8%. This suggests that incorporating additional employee job benefits, such as employer pensions contributions into the model, could further increase the return to 4.87% (Fig. 13).

5. Discussion

This study evaluates the social and environmental impacts of major renewable energy technologies development under UK's CfD scheme from 2016 to 2025. We focus upon CO_2 reduction as an indicator of environmental benefit and job creation as an indicator for social benefit. The findings indicate that combined social and environmental benefits for offshore wind cover 0.35 of its CfD scheme payments. This relative underperformance lies in the high capital expenditure needed and subsequently the higher strike price. However, the decline in the offshore wind strike prices over time offset the gradual decline of grid decarbonisation and subsequent environmental impact, ultimately improving offshore wind performance in AR-2 to 4.37.

Interestingly, the socio-environmental return for offshore wind under the CfD scheme is nearly equivalent to the ROC scheme, with a 0.35 return [69]. This reflects the interactions of two opposing and broadly offsetting forces. First, support scheme payments declined with the transition from ROC to CfD scheme, largely driven by a technology learning curve impact, where cost of technology decline as cumulative deployment increases. Second, grid CO_2 emissions intensity fell from 0.47 tCO_2/MWh (2009–2015) to 0.25 tCO_2/MWh (2016–2025). While grid decarbonisation as a source of indirect environmental impact is expected to further decrease emissions intensity, the rising social cost of CO_2 emissions will likely counteract this effect. Consequently, the net prospective environmental impact will ultimately depend upon the relative magnitude of these two drivers. To enhance the social return of offshore wind, expanding job opportunities and strengthening domestic turbine manufacturing capability within the domestic offshore wind technology value chain is essential. For instance, doubling the offshore wind employment factor can boost its socio-environmental return from 0.35 to 0.39.

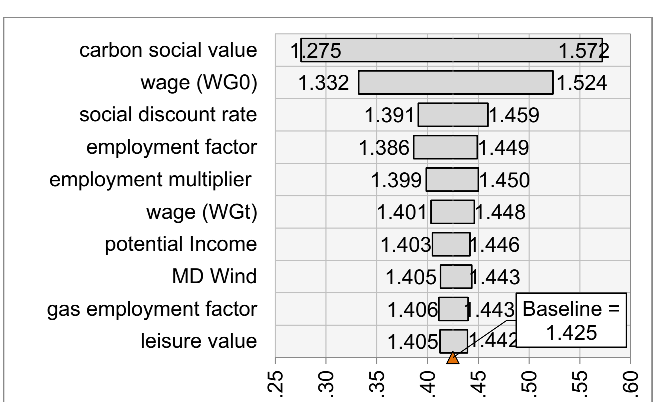

Fig. 12. Tornado plot presenting sensitivity analysis results for onshore wind socio-environmental return, highlighting dominant drivers of uncertainty.

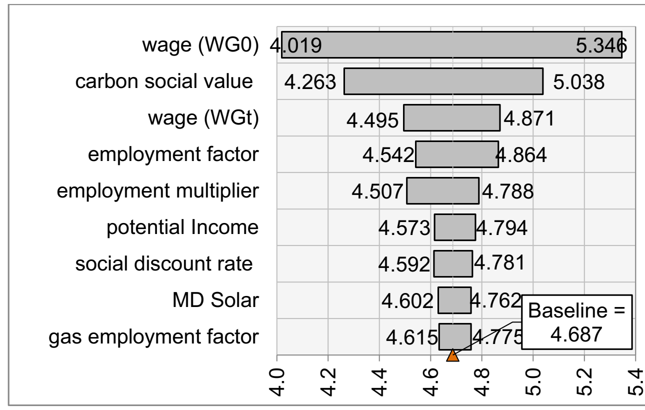

Fig. 13. Tornado plot illustrating the sensitivity of the socio-environmental return of solar-PV to ±20% variations in key model inputs, based on Monte Carlo simulation results.

Onshore wind accounted for 7.7% of the UK's total electricity generation under the CfD scheme, with a discounted CfD scheme payment of £35/MWh. This is cheaper than the offshore wind CfD scheme at £82/MWh, resulting in a return nearly two times higher. The share of onshore wind in the UK's energy supply is expanding, particularly in Scotland, the East of England, and the Midlands. However, despite recent legislative efforts to ease planning approval restrictions [104], significant sociocultural barriers to onshore wind planning often result from community opposition to proposals and subsequent political backlash against implementation plans for onshore wind [105], stalling its expansion. Though policy measures such as stronger mechanisms for public participation in planning, community benefits and shared ownership models will likely improve social acceptance and the consequent uptake of onshore wind [106,107], robust social impact-oriented policies to improve regional employment and upskilling of local communities will also further improve the relative social and environmental impact profile of onshore wind and support in upscaling a renewable energy transition.

Despite the low load factor of solar-PV energy, it presents the highest return at an average of 4.8, driven by a higher employment impact and lower CfD payments. However, similar to onshore wind, public opposition and planning restrictions towards large solar-PV farms are a key barrier to deployment, particularly given the potential energy-food land use conflicts that emerge when solar-PV is constructed at scale on previous arable land [108,109]. Nevertheless, unlike onshore wind, solar-PV is also widely deployed in domestic and commercial microscale applications that do not require planning approvals in the same way, and new policies for housebuilders to incorporate solar-PV into roof design will improve uptake without the need for further planning policy change to rural land. However, demonstrable solar-PV contributions to the socio-environmental return under the CfD scheme could be a decisive factor for encouraging developer commitment to solar-PV installation and supporting planning authority approvals in rural communities. The positive benefits could be further enhanced by encouraging supply-push policies to subsidise domestic solar-PV technology manufacture, thus improving employment opportunities, and reinforcing domestic supply chains for solar-PV construction particularly in the South-East and South-West of England where solar-PV energy potential is highest.

The arithmetic average return for all three sources of energy is 2.15, while the weighted average ratio adjusted for electricity generation is 0.45. These results suggest that the environmental and social impact of renewable energy under the CfD scheme remain suboptimal and would benefit from enhancing social and environmental outcome. Moreover, irrespective of CfD scheme payments, solar-PV, offshore, and onshore wind offers the socio-environmental benefits averaged at £28/MWh, £20/MWh, and £18/MWh, respectively. The unweighted average benefits amounted to £23/MWh for all technologies. However, the weighted average benefit is £21/MWh. Comparing the social and environmental impact with the LCOE in 2025 [110], shows that solar-PV technology impact could cover 48% of the LCOE, for offshore wind and onshore wind it is 33%, and 21%, respectively.

Our results suggest that the social and environmental impact of renewable energy under the CfD scheme is sub-optimal. However, accounting for a wider range of benefits may indicate a more optimal outcome. For example, additional benefits could include reduction in energy bills [52,111], improvement in energy security, and reduced reliance on fossil fuel imports. The CfD scheme would benefit from complementary policies that help to realise these benefits more fully, such the development of a formalised carbon market and mechanisms to monetise indirect CO_2 emissions reduction revenue. By contrast, many social benefits are non-monetary. However, the results of this analysis can still inform public policy design and government employment and skills strategy.

With the UK government considering the integration of sustainability and non-monetised aspects of renewable energy policy through the proposed Clean Industry Bonus (CIB) mechanism. CIBs were formerly known as 'Sustainable Industry Rewards' (SIRs). The CIBs will be integrated into the Round 7 allocation of the CfDs [30,112]. The findings of this study support informed CfD policymaking by highlighting the relative social and environmental benefits of each renewable energy technology. Realising increased social and environmental impacts from renewable energy technologies under the CfD scheme requires coordinated engagement with stakeholders across the supply chain and with affected communities that may resist renewables development. This is necessary to ensure that appropriate supporting policy for local skills development, labour transition, and public participation are in place in order to achieving a *just* low carbon energy transition for affected communities.

6. Conclusions and policy recommendations

This study examines the social and environmental implications of key renewable energy technologies under the UK's CfD scheme. The findings underscore the importance of quantifying regional employment social benefit and evaluating indirect CO_2 emissions reduction impacts into energy policy evaluation to strengthen evidence-based policymaking. Our findings show that the CfD scheme should focus on the socio-environmental contributions of renewable energy policies, particularly in regions with higher unemployment rates, such as the North East of England. Policy intervention should emphasise the development of domestic manufacturing supply chains and capabilities, thereby reducing reliance on turbine and solar-PV imports. Such measures foster job creation and workforce upskilling, regional economic development, and contribute to national energy security and energy sovereignty goals under conditions of turbulent fossil fuel geopolitics.

Renewable energy policy actions should also facilitate regional deployment to ensure a just transition. These include changes to planning policies that make it easier for local authorities to approve developments in areas identified as suitable in local or neighbourhood plans, as long as any concerns raised by local communities have been addressed, and sufficient community support is demonstrated [104]. Mechanisms for community participation, community benefits-sharing, and shared ownership models will likely improve community support for wind and solar-PV and thus facilitate the expansion of renewable energy capacity under current planning rules.

Broader social and environmental benefits should be considered when choosing between technology support decisions to enhance regional social welfare. An adapted CfD scheme can thus support a just transition for workers in fossil fuel-intensive regions by facilitating skills development and employment opportunities across renewable energy manufacturing sector. This study proposes the introduction of the Clean Industry Bonus (formerly Sustainable Industry Rewards) into the future ARs of CfD allocation, will help to capture the non-monetised benefits of renewable energy technologies. Such an approach will support achieving a sustainable and equitable energy transition in the UK and other countries implementing equivalent renewable energy economic policies.

Future research should expand the scope to include wider ecosystemic and biodiversity impacts, as well as a broader array of social impacts including skills development, public health outcomes, and potential inequality reduction. Additionally, further investigation into economic dimensions such as demand-side dynamics, fossil fuel import prices, impacts on consumer energy prices, and links to consumer perceptions and social acceptance of renewable energy technologies in situ would provide a more comprehensive understanding of the socio-environmental implications of the broader renewable energy policy landscape in which CfDs sit.

CRediT authorship contribution statement

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

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