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Who pays for BECCS and DACCS in the UK: designing equitable climate policy

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ABSTRACT

The UK government's net-zero commitment assumes the use of bio-energy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS). Quantifying where the costs of funding these technologies fall – and their magnitude – provides greater insight into potential fairness of future government policies. Using a microsimulation model, this study is the first to evaluate the potential distributional impacts. We consider the distributional incidence and magnitude on household income deciles if the costs for deploying and operating BECCS and DACCS are placed on different sectors of the economy via a range of viable policy funding options. Using existing and novel policy funding options, we demonstrate that levying the costs entirely on the household energy bill is the most regressive of the options considered. We find aviation to be an important point of intervention from a distributional perspective. Higher-income households have larger aviation carbon footprints than lower-income households, meaning passing costs onto households via aviation alone could help fund BECCS and DACCS while having minimal impacts on social welfare. Funding BECCS and DACCS via income tax emerged as the only progressive way of apportioning costs across income deciles. As the benefits of carbon removal accrue to society as a whole, there is further argument that the costs should be shared across society in the fairest way possible. However, such an approach has the potential to blunt the price signal that polluters face. In reality, some pass-through cost may be desirable to adhere to equity principles under a polluter pays principle and to create an incentive for polluters to switch to cleaner inputs and adopt low-carbon technologies.

Key policy insights:



- This study is the first to evaluate distributional incidence and magnitude of costs to households, if costs for deploying and operating BECCS and DACCS are placed on different sectors of the economy.
- Recovering policy costs via income tax provides a progressive option to fund BECCS and DACCS.
- All modelled alternative funding options result in regressive outcomes where low-income households pay disproportionately more towards the costs of BECCS and DACCS.
- Funding BECCS and DACCS through levies on household energy bills further entrenches inequality; spend on electricity as a share of income is disproportionately high for low-income households.


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1. Introduction

Achieving global net-zero emissions is essential to keep global warming to 1.5 degrees Celsius and limit the worst impacts of climate change. The Special Report on Global Warming of 1.5°C by the Intergovernmental Panel on Climate Change (IPCC) concluded that ‘limiting temperature rise to around 1.5 degrees implies reaching net-zero emissions of CO₂ by mid-century’ (IPCC, 2018).

The net-zero commitment by the UK and countries including Sweden, Canada, and New Zealand, assumes the use of greenhouse gas removal (GGR). Methods of GGR are often separated into nature-based and engineered/technological approaches. The former includes afforestation, soil carbon sequestration, enhanced ocean weather, and biochar. For the latter, the dominant technologies are bio-energy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS). Because ‘nature-based’ and ‘technological’ classifications have significant political implications, alternative, value-neutral ‘ecosystem-based’ and ‘geochemical-based’ classifications are also proposed (Schenuit et al., 2021). In the latest IPCC assessment, BECCS and DACCS are considered as geochemical and chemical-based removal processes respectively, with long temporal storage a common characteristic as CO₂ is stored in geological formations rather than in vegetation or soils (IPCC, 2022). Recognizing this, we refer to the focus of this paper as BECCS and DACCS (from here on, referred to as ‘GGR technologies’¹).

The UK Climate Change Committee (CCC)² have produced five net-zero scenarios for the country and all include varying amounts of GGR deployment (CCC, 2020b). This is consistent with almost all modelled emissions scenarios aligning with the Paris Agreement’s target of limiting global temperature increase to well below 2°C. Strong cases for the use of GGR have been made (Bellamy & Geden, 2019; Fuss et al., 2020) and 87% of IPCC’s Integrated Assessment Model (IAM) pathways rely on negative emissions (Fuss et al., 2014; IPCC, 2022). The latest IPCC report starkly warns that the deployment of GGR is ‘unavoidable’ if net zero CO₂ is to be achieved. The UK Government recently set the ambition of deploying at least 5 MtCO₂-yr⁻¹ of ‘engineered’³ removals by 2030 (HM Government, 2021). The IPCC (2022) now goes further stating that,

for countries with emissions targets aiming for net-zero or lower, the core governance question is not whether CDR (carbon dioxide removal) should be mobilised, but which CDR methods governments want to see deployed by whom, by when, at which volumes and in which ways.

This reflects a more nuanced debate, reframing the question of whether we should use GGR, to how do we do it in sustainable and equitable manner.

Despite the prevalence of GGR technology in Paris-consistent scenarios, and the UK’s own net-zero technological pathway, there is neither sufficient regulatory support for emerging technologies in the UK, nor an understanding of important governance questions such as how they are funded and who bears the cost. As the UK looks ahead to meeting its net-zero target – with BECCS and DACCS playing a role – it is important to understand how the costs of funding these technologies are distributed across society.

When designing policy to fund GGR technologies, there are a number of concerns to address and design choices to make. Firstly, in line with the CCC’s recommendation to HM Treasury, policy costs should be funded fairly otherwise the policy may fail (HM Treasury, 2020). Here we examine fairness by assessing whether the policy is regressive or not. Secondly, how should the cost of GGRs be allocated to sectors and ultimately households who consume the goods and services they provide? Thirdly, should households be liable only for the cost of achieving net-zero emissions in the UK, or is there a requirement to fund net-negative emissions? Fourthly, should carbon emissions or income be used to

¹We focus exclusively on BECCS and DACCS among GGR technologies. The CCC considers wood in construction in addition to BECCS and DACCS in their modelling of GGR technologies but assumes it will be deployed at a small scale and its costs accounted for in the land use, manufacturing and construction sectors (CCC, 2020a). We assume the costs of wood in construction are negligible and impact on the distributional considerations are minor.

²An independent statutory body which advises the UK Government on programmes made in reducing greenhouse gas emissions.

³The UK Government’s Net Zero Strategy considers DACCS, BECCS, wood in construction, biochar, and enhanced weathering as part of engineering-based removals.

differentiate the amount households pay? Finally, should the cost fall on both UK households⁴ and the Government?

1.1. Methods for funding GGR technologies

The rationale for assigning costs to consumers stems from the fundamental market failure at the core of the climate problem, namely that emitters of greenhouse gases are not confronted with the environmental costs caused by their actions. In accordance with the polluter-pays-principle, carbon pricing changes relative prices of all goods and services. The expectation is that once emitters are confronted with the full cost of their actions through a carbon price, they are incentivised to reduce demand for carbon intensive products (Baranzini et al., 2017). As carbon pricing is the most explicit way to assign costs to consumers, this is where the existing literature examining distributional impacts has focused (Browne et al., 2013; Cronin et al., 2019; Douenne, 2018; Feng et al., 2010; Gough et al., 2011). These authors conclude that without compensation measures, such as hypothecating revenues back to consumers, the distributive effect of a carbon tax – i.e. the vertical variation in impact along the income dimension – is ‘regressive’ as the impacts of carbon pricing policies often fall disproportionately on poorer households. While the wealthier households produce more carbon emissions in absolute terms (due to greater overall consumption), carbon-intensive spending as a proportion of income is higher for poorer households (Gough et al., 2011).

Whilst this holds true for developed economies with relatively higher incomes (Dorband et al., 2019), results from meta-analysis on the distributional impacts of carbon prices indicate a significantly increased likelihood of progressive distributional outcomes for low-income countries (Ohlendorf et al., 2021). It is important to recognize that there is large inequality in international and intranational energy footprints between income groups and across consumption categories (Oswald et al., 2020). Vertical distributive effects are not uniformly regressive across all consumption categories, which we discuss later in the paper.

Depending on the sectors/consumption categories on which costs of GGRs are placed, and in the absence of measures to mitigate socially regressive impacts, there is a risk that the cost as a proportion of income will be higher for low-income groups than higher groups. Our focus on BECCS and DACCS is particularly pertinent as evidence on public perceptions suggest these GGR techniques are currently seen as controversial and incompatible with prevailing visions of decarbonization (Cox et al., 2020). In contrast, afforestation and other land-based GGR processes are *a priori* popular (Climate Assembly UK, 2020; Lezaun et al., 2021) despite the contested nature of what constitutes ‘natural’. BECCS and DACCS could be susceptible to public opposition if the policy for funding and deployment fails to account for undesirable distributional consequences (Bellamy et al., 2019).

Furthermore, for the UK to meet net-zero, the quantity of removals and total investment required for BECCS and DACCS is estimated to exceed that of land based biological removal processes. The CCC’s recommended pathway to net-zero for the UK requires BECCS and DACCS to remove 58 MtCO₂yr⁻¹ in 2050 where land-based biological sinks account for 39 MtCO₂yr⁻¹ of removals (CCC, 2020a). Due to higher average unit abatement costs and higher quantities, this translates to estimated net investment costs of £2.38 bn_{yr}⁻¹ in 2035 increasing to £5.73 bn_{yr}⁻¹ by 2050 for scaling up BECCS and DACCS, compared to £1.4 bn_{yr}⁻¹ of investment costs in 2035 continuing at a similar level through to 2050 for land-based methods (including afforestation and peat restoration) (Ibid.).

This emerging policy context requires a deeper understanding of where costs fall and how Government policy can be designed to mitigate distributional impacts for GGRs; in particular, BECCS and DACCS. There is an opportunity to develop a fair and enduring policy framework for GGRs that fosters high levels of public legitimacy.

Although research on key themes relating to the social and political dimensions of GGR feasibility include equity and justice (Forster et al., 2020), the methodological approach is qualitative, largely stemming from workshops, interviews, and surveys (Bellamy & Healey, 2018; Low & Schäfer, 2020; Rickels et al., 2019).

⁴References throughout the paper to the cost on households should be interpreted as the *direct* cost on households. The distinction is important given households as taxpayers would indirectly bear the cost on the Government as well to a large extent.

Cotton (2017) suggests that public reactions to GGR are influenced by the distribution of benefits, costs, and compensation. This is echoed in public deliberation exercises where the topics of fairness and equity often arise, with people reacting negatively to proposals that are perceived to engender unfair distribution of risks and benefits (Bellamy et al., 2017; Demski et al., 2015). Quantitative analysis on the distribution of costs have been largely neglected. In their recent paper Honegger et al. (2021) ask the question ‘Who is paying for Carbon Dioxide Removal?’ Yet despite having almost the same title as this paper, it does not explore the distributional impacts.

In this paper, we quantitatively examine the potential distributional impacts to UK households if costs for deploying GGR technologies – namely, BECCS and DACCS – are placed on different sectors of the economy. Specifically, we calculate absolute monetary impact and the proportion of total disposable income paid by each income decile towards funding GGR technologies under four policy funding options:

- Option 1 – Polluter-pays-principle: assumes that the cost of GGR technologies is allocated to sectors based on their proportion of residual emissions.
- Option 2 – Carbon Contract for Difference (CfD)⁵: assumes that the cost of GGR technologies is allocated via a levy on household energy bills.
- Option 3 – Multi-sector government contract: assumes that the cost of GGR technologies is allocated to sectors based on end-use application (for example, BECCS power in the power sector, BECCS energy from waste (EFW) in the waste sector).
- Option 4 – Income tax: assumes that household contributions to fund GGR technologies are weighted by the household’s contribution to total UK income tax payments.

This paper aims to help policymakers identify the distributional impacts of different policy funding options for BECCS and DACCS. The paper is organized as follows: Section 2 outlines the analytical approach and the assumptions for GGR deployment used in the paper, including a detailed description of the key data sources; Section 3 describes the results of our analysis including an assessment of distributional costs by income decile; Section 4 discusses the implications of the results and areas for further research; and Section 5 concludes.

2. Data and methodology

2.1. Overview

For this analysis, the costs of GGR technologies (BECCS and DACCS) are assumed to be directly passed on to the consumers of the goods and services provided by UK industries. If GGR technologies are costed at a price-per-tonne of abated carbon, the cost to the consumer will be determined by the portion of their associated carbon footprint that can be traced back to domestic industries.

Determining the distributional impacts of GGR technologies to UK households requires a model capable of tracing UK industrial emissions to the point of consumption. We use a static microsimulation model focusing on two years – 2035 and 2050 – which requires the following data inputs:

2.2. A static microsimulation approach to calculate distributional impacts

A common method for modelling economic effects of policy change uses a computational general equilibrium model (CGE) (OECD, 2021; Ohlendorf et al., 2021). The CGE model finds a future equilibrium solution resulting from the effects of the policy change. In this study, we consider the implications of different approaches to fund GGR technologies using a static microsimulation model. Microsimulation models, unlike the CGE models, allow

⁵This is the name for an existing mechanism designed to provide a subsidy above a reference price for negative emissions up to a contractually arranged strike price in £/tCO₂. The reference price can be linked to a carbon price or negative emissions market. See Element Energy (2021) for more details.

Table 1. Data requirements and sources.

Data requirements	Source
Estimated cost-per-tonne for GGR technologies in 2035 and 2050	CCC Sixth Carbon Budget (CCC, 2020b)
Estimated abatement potential by GGR technologies in 2035 and 2050	CCC Sixth Carbon Budget (CCC, 2020b)
Application of GGR technologies by end-use or intermediary use sector	CCC Sixth Carbon Budget (CCC, 2020b)
Estimates of greenhouse gas emissions by UK industries in 2018, 2035 and 2050	CCC Sixth Carbon Budget (CCC, 2020b) & UKMRIO framework (Owen & Barrett, 2020)
Estimates of household consumption in 2018, 2035 and 2050	CCC Sixth Carbon Budget (CCC, 2020b) & Living costs and food survey 2018 (UK Data Service, 2019)

a comprehensive analysis of distributional effects at the micro level, for multiple household types (Berry, 2019; Clauss & Schubert, 2011).

Our model takes estimates of domestic emissions by income decile, for the years 2035 and 2050 (calculated using the UKMRIO framework, see section 2.4), alongside information on the portion of residual emissions abated by BECCS and DACCS and associated costs (from the CCC's Sixth Carbon Budget advice, see section 2.3). The costs of abatement through BECCS and DACCS are assigned to end-users (UK households, UK Government, UK capital expenditure and exports) based on the portion of abated industrial emissions present in the supply chain of goods consumed. Household consumption is calculated from the Living Costs and Food Survey and the CCC's Sixth Carbon Budget advice (see section 2.5). This approach allows estimation of the economic incidence of deploying and operating GGR technologies by household income decile.

2.3. The climate change committee's sixth carbon budget advice

The assumptions in this study for modelling the distributional impacts of funding GGR technologies across sectors are underpinned by the CCC's Sixth Carbon Budget (CCC, 2020b). Data specified in Table 1 is extracted for each of the CCC's five net-zero scenarios (see Supporting Information 1.1.1 for further detail).

Our model is calibrated so that end-users are liable for achieving not just net-zero but net-negative emissions (where entailed by the chosen CCC scenario). Given that the UK is a wealthy, developed nation with high historical emissions, the CCC concludes that its emissions reductions targets should be more ambitious than the world as a whole (CCC, 2019).

2.3.1. Balanced net zero

Balanced Net Zero (BNZ) is the CCC's recommended scenario for the UK to meet its net-zero target and underpins this paper's results. The following figures show the residual emissions (Figure 1) and the abatement technologies and their associated cost used for the BNZ scenario in 2035 and 2050 (Figure 2).

In 2035, the overall deployment of GGR technologies is relatively small, abating ~10% of residual emissions in total. From 2035 to 2050, residual emissions in absolute terms drop by almost one-third while the proportion of residual emissions removed by GGR technologies rises to almost 80%.⁶

Under the BNZ scenario, BECCS energy-from-waste is the costliest GGR technology in 2035 where BECCS hydrogen, biofuels, and bio-methane are the least costly. All GGR technologies (except BECCS in industry) are expected to decrease in costs from 2035 to 2050. DACCS emerges as the costliest option in 2050. In 2035, under the BNZ scenario, the total costs of BECCS and DACCS is £2.38 bn yr^{-1} , rising to £5.73 bn yr^{-1} in 2050.

2.4. Calculating product multipliers using the UK multiregional input-output (UKMRIO) framework

The UK's carbon footprint⁷ is an official statistic calculated by the University of Leeds (Defra, 2021). The calculation uses an environmentally-extended multiregional input-output (MRIO) framework (the

⁶Note that the residual emissions in 2050 that are not abated by GGR technologies are abated by other means given the BNZ scenario is designed to meet net-zero emissions by 2050.

⁷Also known as the consumption-based emissions account.

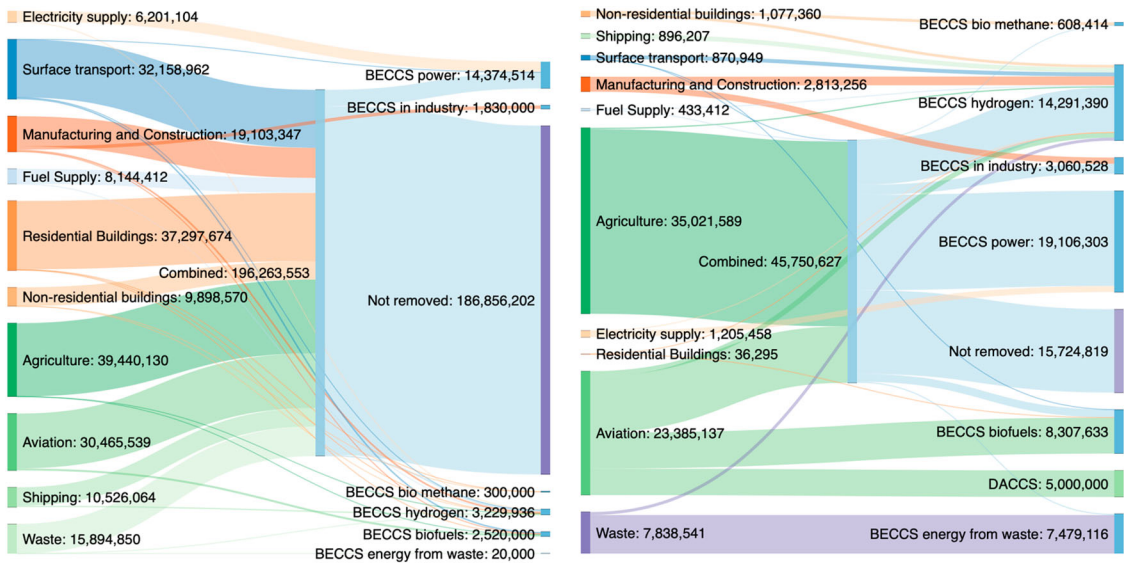


Figure 1. Residual emissions and the abatement technologies used for the BNZ scenario in 2035 (left) and 2050 (right) in tonnes CO₂e. Data from (CCC, 2020b).

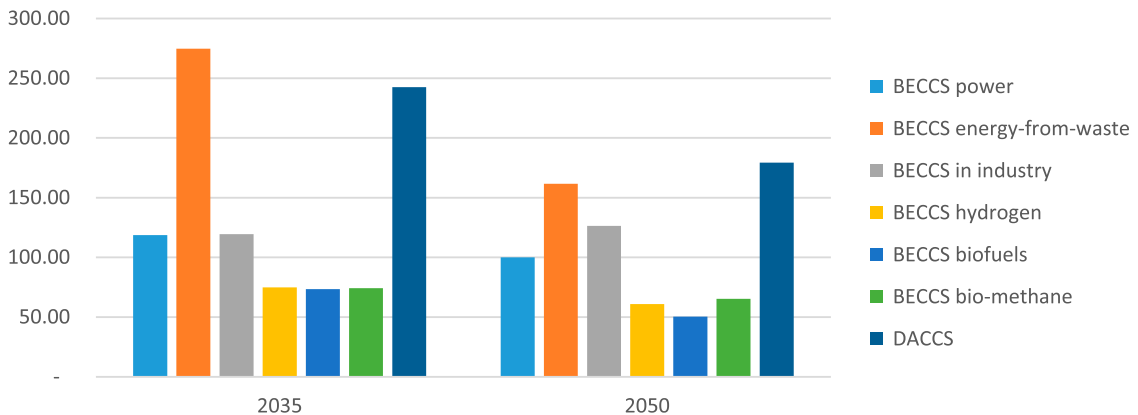


Figure 2. Average abatement costs by GGR technology for the BNZ scenario (£ per tonne CO₂e). Data from (CCC, 2020b).

UKMRIO⁸). MRIO databases make the link between the environmental impacts associated with production techniques and the consumers of products. The fundamental Leontief equation,⁹ $x = (I - A)^{-1}y$ (Miller & Blair, 2009), indicates the inter-industry requirements of each sector to deliver a unit of output to final demand. Since the 1960s, the IO framework has been extended¹⁰ to account for increases in the pollution associated with industrial production due to a change in final demand.

The UKMRIO calculates domestic carbon footprints for 2035 and 2050 by changing some model inputs (see Owen et al., 2021 for details). Residual emissions data from the CCC scenarios (CCC, 2020b) replaces the UK

⁸For further discussion of the UKMRIO database, including additional notes on construction and application, see Barrett et al., 2013; Hardt et al., 2018; Lenzen et al., 2010; Owen et al., 2018; Sakai et al., 2017; Scott et al., 2018; and Wiedmann et al., 2010, and the Supporting Information (SI) for this article.

⁹ x and y are vectors of total output and final demand, respectively, I is the identity matrix, and A is the technical coefficient matrix, which shows the inter-industry requirements. $(I - A)^{-1}$ is known as the Leontief inverse.

¹⁰If f is a row vector of annual energy used by each industrial sector let $e = f\hat{x}^{-1}$. Then, $ex = e(I - A)^{-1}y$, which simplifies to $F = eLy$ where F is the energy required to meet final demand y .

industrial emissions, and emissions from the rest of the world are set to zero. For this study we calculate the carbon footprint associated with UK household spend. Surveys of household spend are aligned with the Input-Output tables. The household footprint by product is then divided by the UK total household spends from an expenditure survey to give a set of $\text{CO}_2\text{e}\text{£}^{-1}$ multipliers.

2.5. Calculating the carbon footprints of equivalised household income deciles using the Living Costs and Food Survey

UK households have been surveyed annually on their weekly expenditure since the 1950s (UK Data Service, 2019). This Living Costs and Food Survey (LCFS) achieves a sample of around 6,000 UK households providing information on household spend on hundreds of product types, household incomes, and composition. We have used 2018 LCFS data to develop an expenditure profile for household income deciles. Before grouping the surveys by raw income, we adjust each survey entry so that the households are identical in composition. This step, known as equivalisation (Gough et al., 2011), allows for comparison of the effects of cost increases on households with different incomes but the same composition. This study uses a modified OECD equivalence scale, as preferred by UK Government, where the reference case (weight = 1) is a two-adult household with no children.¹¹

We apply the multipliers generated from the UKMRIO to the spend profiles to calculate domestic carbon footprints (see Owen & Barrett, 2020 for further examples of this methodology). Figure 3 shows the flow of domestic emissions from the UK's industrial sectors (left) to the end-users (right). Emissions are either 'consumed' by the household deciles or used for UK Government, UK capital expenditure or exports. The domestic carbon footprint of a household in equivalised income decile 1 is less than half that of a household in decile 10. Emissions associated with housing, power, and transportation make up the majority of the domestic carbon footprint. Housing and power emissions are 63% of decile 1 and 37% of decile 10, whereas transportation is 30% of decile 10 and 25% of decile 1.

Carbon footprints for 2035 and 2050 are calculated by changing fuel spends according to the household energy demand data from the CCC scenarios (CCC, 2020b). No other changes to household spend are made.

2.6. Comparing different policy funding options for GGR technologies

We constructed four policy funding options to assess the distributional impacts of paying for BECCS and DACCS (see Table 2). This is not an exhaustive list of policy options. Policy funding options 1–3 have been designed to reflect viable GGR business models discussed in the literature (Element Energy, 2021; UK Government, 2021; Vivid Economics, 2019) and under consideration by the UK Government (UK Government, 2021). Support for low-carbon generation in the UK is currently levied entirely on the electricity bill, but the Government has committed to the rebalancing of policy costs from electricity bills to gas bills over this decade in its Net Zero Strategy of October 2021 (HM Government, 2021). We designed option 2, Carbon CfD, to allocate costs of BECCS and DACCS onto the entire household energy bill (electricity and gas) to better reflect forthcoming policy changes. While option 4, income tax, has not been considered in the Government consultation on GGRs (UK Government, 2021), it demonstrates an alternative funding model that the government may wish to consider, and was suggested by Owen and Barrett (2020) as a potential approach. Note that for options 1 and 3, the costs of technologies are passed to the end-consumers of the source sectors. These consumers are UK households or Government, so the total cost to households is less than in options 2 and 4.

Table 2 classifies the four policy funding options into three operational approaches based on research by Element Energy (2021). 'Government interventions' describes a mechanism where the outcome is prescribed

¹¹Each household in the Living Costs and Food Survey is assigned an equivalence factor. Households with a single adult score 0.67, each subsequent adult adds 0.33 and children under the age of 14 score 0.2. So for example, a household of 2 adults and 2 children scores 1.4. Income and expenditure is divided by the equivalence factor to ensure that each survey is equivalent to a household of 2 adults and no children. From this point on when we refer to household income groups we mean equivalised household income groups

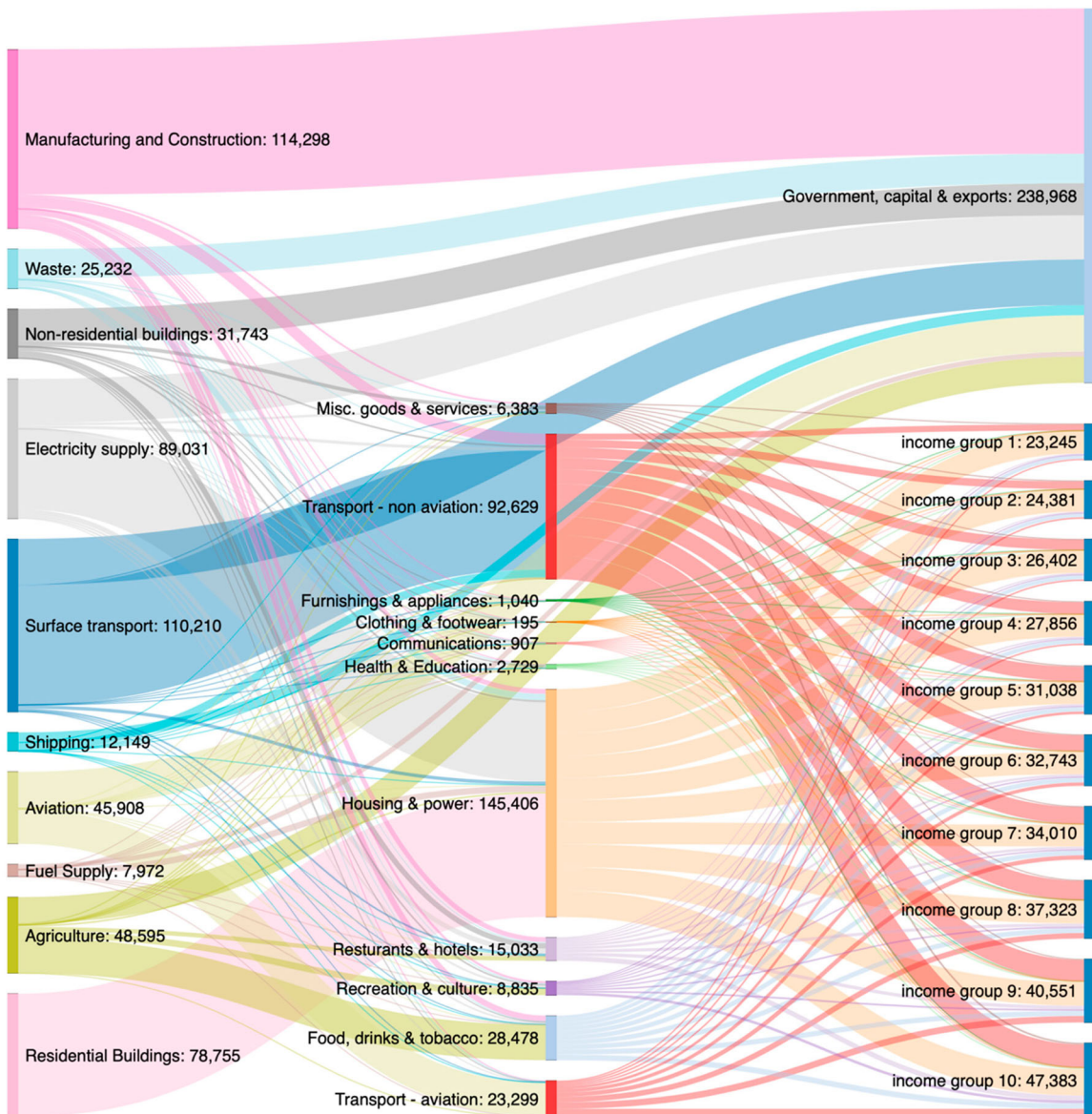







Figure 3. UK domestic emissions by source sector (right) and end-use (left) 2018 in ktonnes CO₂e. Data from University of Leeds.

by the government, whereas ‘market-based’ describes the other end of the spectrum with outcomes predominately driven by market competition. ‘Contracted’ mechanisms involve a hybrid approach where government intervention and market-based factors both drive outcomes.

2.7. Methodological limitations

This study does not estimate changes in household demand resulting from a change in the price of goods. It instead provides robust comparison of the implications of different policy funding options. One possible long-run change might be households changing the pattern of their expenditure due to having less money available to spend. These changes in spend may differ according to a household’s level of income. Income elasticities of demand could show the effect of a change in income, but predicting these rebound effects is beyond the scope of this paper.

Table 2. Summary of the four policy funding options, the mechanisms required, operational approach, and the strength of Government intervention needed.

Policy funding option	Description	Mechanism	Operational approach	Strength of Government intervention
1, Polluter-pays-principle	Assumes that the cost of GGR technologies in 2035 and 2050 is allocated to sectors based on their proportion of residual emissions in 2035 and 2050. The cost falls on UK households and the Government ^a	GGR obligation where producers are obliged to purchase GGR credits and must demonstrate that a percentage of their emissions are offset by GGR. Carbon markets provide a mechanism where polluters purchase GGR credit directly from producers.	Market-based 	LOW  HIGH
2, Carbon CfD	Assumes that the cost of GGR technologies in 2035 and 2050 is levied entirely on household energy bills. The cost falls on UK households.	All GGR contracted via a carbon CfD or GGR service contract. Both mechanisms are funded via a levy on household energy bills (covering both electricity and gas).	Contracted 	
3, Multi sector government contract	Assumes that the cost of GGR technologies in 2035 and 2050 is allocated to sectors based on end-use application. The cost falls on UK households and the Government.	GGR technologies are funded based on end-use application. For example, BECCS power is contracted via power sector contracts, BECCS EFW through waste sector contracts, and BECCS in industry via the industrial sector. This could be operationalized using bilateral sector contracts that reward additional low-carbon products.	Contracted 	
4, Income tax	Assumes that the cost of GGR technologies in 2035 and 2050 is funded via income tax. The cost falls on UK households.	Household contributions to funding GGR technologies are weighted by the household's contribution to total UK income tax payments.	Government interventions 	

Note: ^aBoth UK households and Government are consumers of products produced by these sectors.

The results reflect upper-bound estimates of the distributional impacts because we make the following assumptions:

- The change in price does not lead consumers to change their consumption habits.
- The proportion of UK goods and services remains constant, i.e. consumers do not switch to purchasing imports in response to a price change on domestic goods and services.
- There is full cost pass-through, whereby firms pass all the cost to consumers, i.e. firms do not absorb any costs or change their production processes.

The upper-bound estimates may be moderated as we only track increased costs due to domestic policy. It is likely that goods where the supply chain sits abroad will also increase in price due to costs of carbon policies in those respective countries. Thus, consumers may experience higher future product prices and higher overall household bills when accounting for imports.

3. Results

While the microsimulation model underlying this paper provides the capability to switch between all five of the CCC's net-zero scenarios, the results presented in this paper are based on the Balanced Net Zero (BNZ) pathway¹² for 2035 and 2050.

¹²See supporting information for an assessment of the other four CCC scenarios.

3.1. Distributional impacts to households

While the total cost of GGRs under the BNZ scenario is constant, the costs to households of different income levels varies under each policy funding option. Firstly, the cost is spread to both households and government in policy funding options 1 (polluter pays) and 3 (multi-sector government contract), but in options 2 (Carbon CfD) and 4 (income tax), households are paying the full costs. This means that the total cost to households is larger for options 2 and 4. And secondly, for options 2 and 4, the cost to households is dependent on the suite of products bought by both household income groups and government, with some consumption items – such as energy – incurring a greater proportional cost than others. When considering the distributional impact of funding BECCS and DACCS, both the absolute annual costs and the proportion of the household's annual income are considered. Thirdly, option 1 has the smallest and flattest incidence as some of the main sectors which bear the costs under this option interact in ways that somewhat mitigate distributional impacts. This becomes especially apparent in 2050 where the majority of costs under this option are apportioned to the agriculture and aviation sector (see Figure 7). As the former represents a higher proportion of household spend for lower income households and the latter a much smaller proportion, this moderates the overall distributional incidence.

Figure 4 shows for the polluter-pays (1) and income tax (4) policy funding options, the richer the household, the more the household contributes to funding GGR technologies in absolute terms. Carbon CfD (option 2) and multi-sector government contract (option 3) are relatively flat with most households contributing similar amounts in absolute terms. Option 4, income tax, has the greatest range in household costs, with decile 1 contributing just £3.63 compared to £306 for decile 10.

By considering the proportion of annual income the households would pay, we assess whether a policy funding option is regressive (shown by a negative gradient) or progressive (positive gradient). Polluter pays (1), Carbon CfD (2), and multi-sector government contract (3) are regressive, with option 2 being the most severely regressive policy. The income tax (4) option is the only policy in this study which leads to a progressive outcome. Going from the most regressive to the progressive option, the lowest income households see their annual contribution fall from £91yr⁻¹ (0.71% of household income) to £3.63 (0.03%). Conversely, the highest

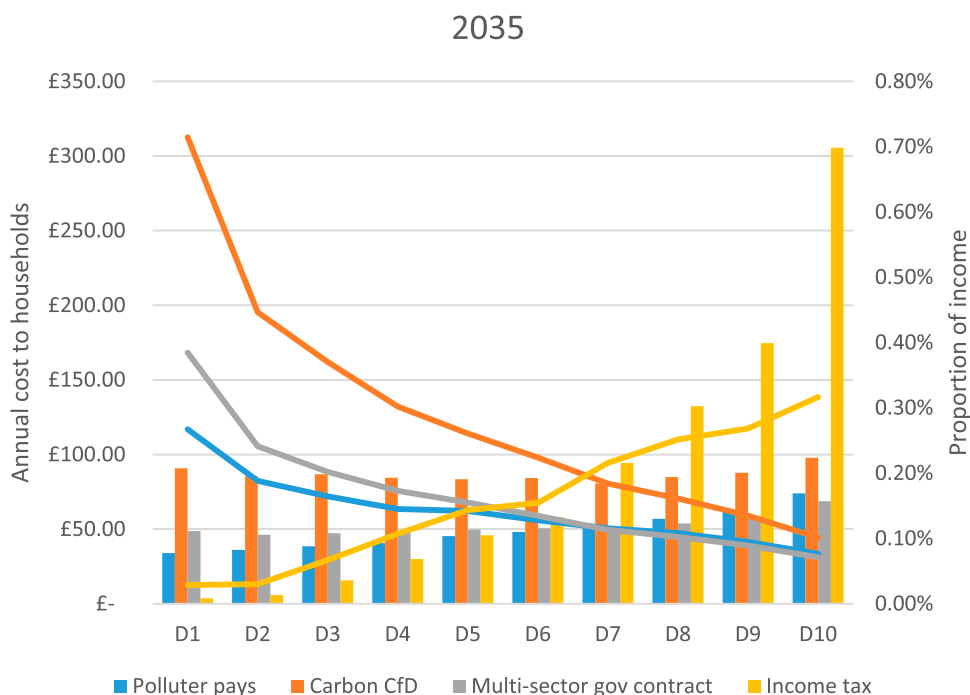


Figure 4. Distributional impacts to equivalised 2-person household income deciles for the BNZ scenario for 2035 under the four policy funding options. Bars show annual costs (in 2018 prices) and lines show proportion of annual income.

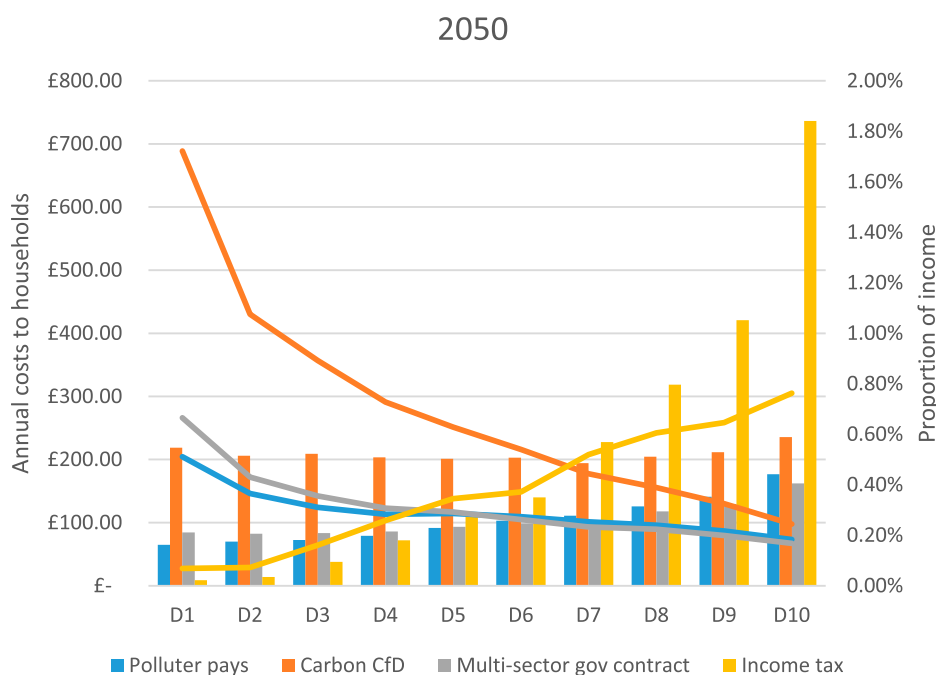


Figure 5. Distributional impacts to equivalised 2-person household income deciles for the BNZ scenario for 2050 under the four policy funding options. Bars show annual costs (in 2018 prices) and lines show proportion of annual income.

income households increase their payments from £98 (0.1% of household income) to £306 (0.32%). Furthermore, the income tax route becomes cheaper for deciles 1–4.

In 2050 (Figure 5), the severity of impacts is more pronounced than in 2035 for all policy funding options. Options 1–3 become more regressive and option 4 is more progressive. Comparing the impact of the progressive policy on decile 10 with the impact of regressive policies on decile 1 can be informative for policy decisions by laying bare the two extremes. As a proportion of income, policy 4 now represents 0.76% of the highest income decile's income which is higher than the 0.51% and 0.67% that policies 1 and 3 represent of the lowest income decile, but still much lower than what policy 2 represents at 1.72% for this lowest income decile.

Both BECCS and DACCS are scaled up from 2035 to 2050 so it is unsurprising that all deciles face higher costs in 2050 under all funding options. However, the relationship between deployment and cost for GGR technologies is not linear given the significant technology cost reductions from 2035 to 2050 assumed in our modelling (see Figure 2) in line with the CCC's projections of the scope for innovation, economies of scale, and learning by doing.

3.2. Explaining the regressive funding options

It is important to illustrate not only the size of the cost, but where costs fall. This section demonstrates how the total cost of BECCS and DACCS for deciles 1 and 10 breaks down into industry and spend sectors for each regressive policy funding option,¹³ revealing areas of spend where policies may have the most distributional impact.

In option 1, (polluter-pays-principle), payments to cover the costs of BECCS and DACCS are proportionately weighted by a sector's residual emissions. Since we assume that increased costs due to purchases of GGR credits are passed to consumers in full, household contributions are proportional to that sector's residual emissions. Figure 6 shows costs in option 1 are passed to households mainly through residential buildings,

¹³Policy funding option (4) cannot be broken down into sectors given costs here fall on the income tax which represents a sector-agnostic form of payment. In other words, the policy cost of funding option (4) is borne by households as taxpayers rather than as consumers of products and services.

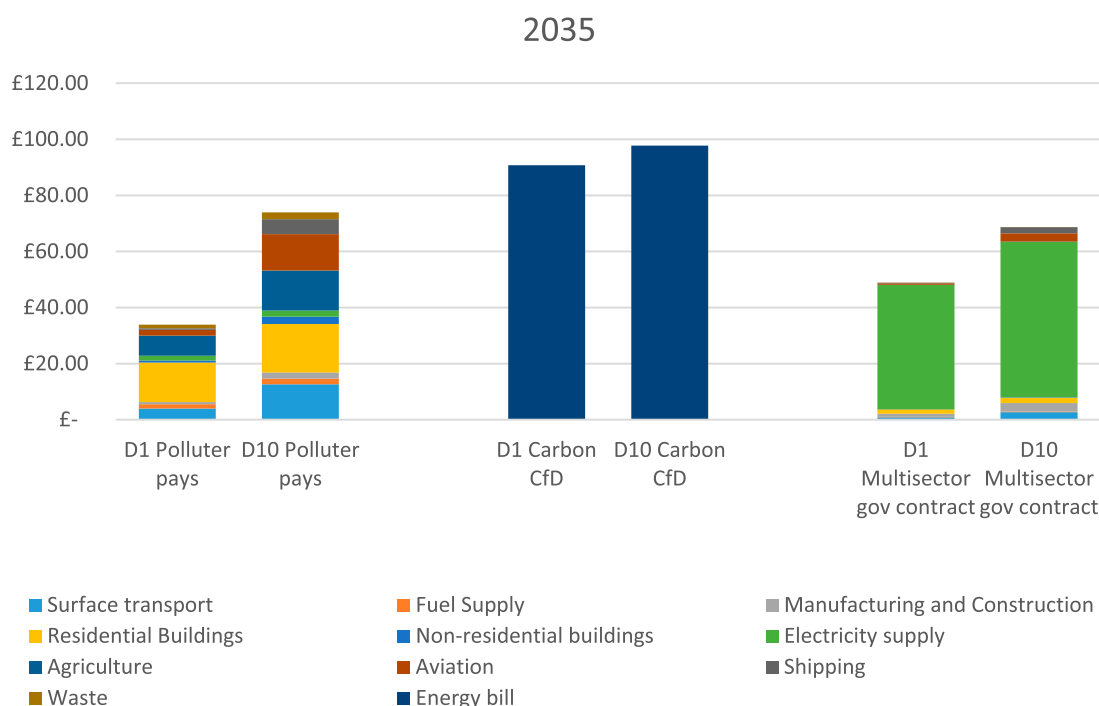


Figure 6. Breakdown of costs by sector for deciles 1 and 10 in 2035 under the CCC's BNZ scenario.

agriculture, aviation, and surface transport sectors. Residential buildings is the largest sector in terms of household payments towards GGR technologies but is a smaller portion of the cost in D10. Aviation requires attention as, despite having a share comparable with some smaller sectors for D1, its share rises through income deciles to the third largest sector in D10, overtaking surface transport.

In option 2, Carbon CfD, the costs of BECCS and DACCS are levied only on energy bills. The associated cost borne by each income decile is therefore proportionate to their energy consumption. This option creates the most regressive outcome of all options when looking at costs as a proportion of income because when households are equivalised to two person units, there is little difference in energy spends across income deciles and the spend on energy then represents a large portion of a low income households disposable income compared to the portion of a high income household.

Option 3, multi-sector government contracts, uses the scale of BECCS and DACCS deployment in end-use sectors as the basis for allocating costs. The policy cost of rewarding additional low-carbon goods and services through bi-lateral sector contracts could be recovered by taxation elsewhere within the respective sectors which we assume is ultimately passed onto households (e.g. in the form of higher prices for carbon-intensive goods). Since BECCS power accounts for most of the total removal from BECCS and DACCS in BNZ (in 2035, 65% of all removals by BECCS and DACCS is in the form of BECCS power), the majority of the costs are allocated to the electricity supply sector. Other sectors are too small to have substantial influence on the overall cost per decile.

Results in option 1 are substantially different in 2050 (Figure 7) because the majority of remaining residual emissions in 2050 are projected to lie in two sectors: aviation and agriculture (see Figure 1). Notably, agriculture makes up 67% of the total cost of BECCS and DACCS for D1, compared to 49% for D10. Residential buildings and surface transport no longer contribute a significant portion of household payments towards GGR technologies, as these sectors are assumed to be largely decarbonized by 2050 under BNZ.¹⁴

¹⁴'Energy bill' category represents the case where costs of GGR technologies are levied directly and in their entirety on the purchase of energy (electricity and gas) as a product. On the other hand, the 'electricity supply' category reflects when GGR costs fall on electricity supply as a source sector of emissions, passed to consumers via the purchase of all products involving electricity in their provision. Figure 3 illustrates how our model allocates emissions from source sectors (left) to consumption products (middle).

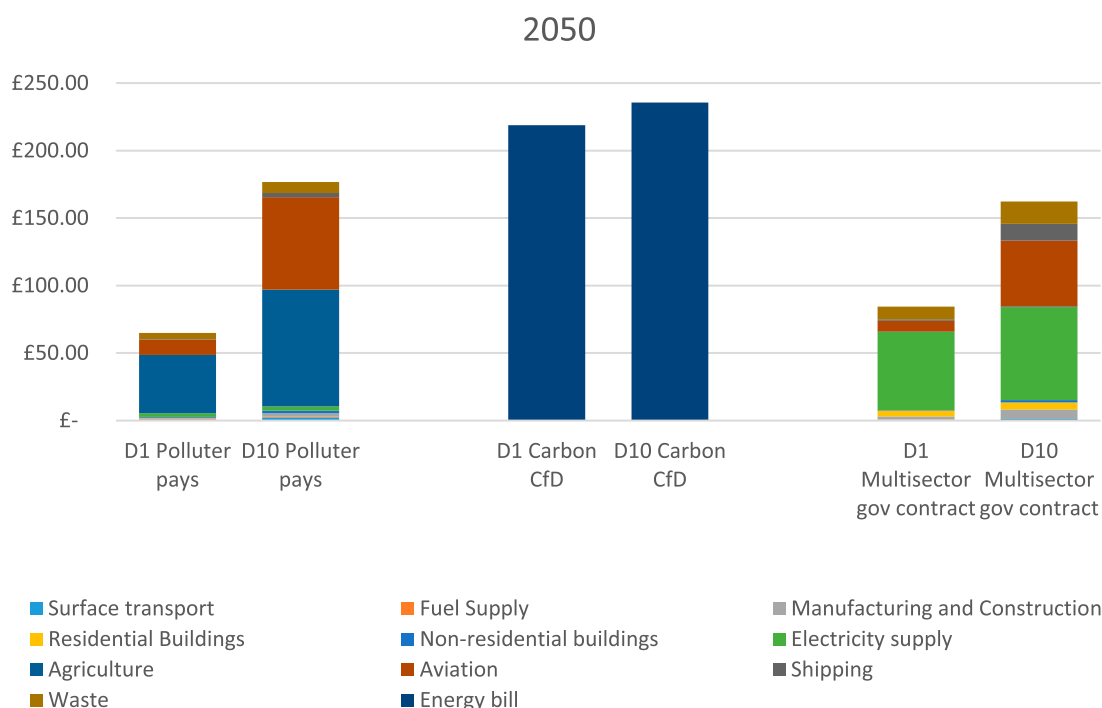


Figure 7. Breakdown of costs by sector for deciles and 1 and 10 in 2050 under the CCC's BNZ scenario.

Option 2 sees increased energy bills in 2050 in line with higher total costs for BECCS and DACCS compared to 2035. In contrast, option 3 is characterized by sectoral changes from 2035 to 2050 following how the CCC projects the end-uses for GGR technologies evolving under BNZ. Similarly, aviation contributes a larger share of household payments towards BECCS and DACCS in 2050 than in 2035, especially for D10. This is in-part down to 5 MtCO₂ removed in 2050 via DACCS – the costliest form of GGR in 2050 – allocated to the aviation sector. Aviation also emerges as the largest end-use for BECCS biofuels in 2050. Waste becomes prominent in 2050, and the use of BECCS EfW is scaled up ~400-fold from 2035 to 2050.

4. Discussion

4.1. The importance of equitable policy design

Designing efficient and effective climate policy for a net-zero world requires careful consideration of how costs and benefits are distributed across society in ways that determine both the immediate political feasibility and the durability of policy options over time. Consumers are sensitive to changes in the cost of provisions such as energy, transport, and food as public protests demonstrate. The carbon pricing literature suggests that perceived (un)fairness is significantly correlated with (low) public acceptability (Maestre-Andrés et al., 2019). Research on car CO₂ taxes suggests that if a policy is perceived to be fair, scepticism about its effectiveness is reduced (Bolderdijk et al., 2017). With bills expected to rise to cover net-zero costs (Smyth, 2021), it is important to examine impacts at different levels of household income. Our analysis uses this analytical framework to help policymakers conceptualize who pays and how they pay. By providing greater insight into the equity of government policies, this provides an opportunity for policymakers to increase policy acceptability.

Understanding the distributional impacts of funding BECCS and DACCS is particularly important as, to date, little empirical evidence exists on how different forms of policy support impact public perceptions of GGR technologies. However, Bellamy and Healey (2018) find that guarantees of higher prices for producers selling energy derived from BECCS were strongly opposed by the public, owing to participants' knowledge of the high-costs imposed on taxpayers by this mechanism.

With the exception of income tax, we find that funding options disproportionately affect low-income households. Figure 8 illustrates that the two funding options with the least regressive impacts (income tax and polluter-pays) have vastly different levels of government intervention. Although this suggests that the level of regressivity is not entirely contingent on the level of government intervention, it demonstrates that the only funding option with a truly progressive outcome is one requiring a greater role for the state. This also demonstrates that even though the polluter-pays-principle – which rests on a key principle of environmental law – is framed as an equitable policy choice, it is not inherently fair. Our results show that low-income households are still disproportionately affected. Put simply, the funding option remains regressive. That said, given that this option (unlike the others presented) raises government revenue, revenue recycling to households could offset regressive impacts. As demonstrated in the carbon pricing literature, how the revenues are used will dictate whether a policy is regressive or progressive and by extension influence the level of public acceptability (Bowen, 2015; Klenert et al., 2018; Klenert & Mattauch, 2016). Indeed, most countries that price carbon have some form of revenue recycling (Burke et al., 2019). Incorporating revenue recycling into a ‘polluter-pays’ approach could ensure equitable outcomes when funding BECCS and DACCS. Revenue raising potential makes a ‘polluter-pays’ approach more politically attractive, especially as it requires limited government funding in times of constrained public finances. However, there are risks to prematurely including GGR in carbon markets, such as the potential for undesirable substitution if emissions removals and emissions reductions are entirely fungible, and the inability of carbon markets to provide sufficient demand pull to drive currently more-costly GGR techniques – such as BECCS and DACCS – to deployment at commercial scales (Burke & Gambhir, 2022).

The policy which has the most regressive distributional impacts bares the most similarity to current government policy for funding low-carbon generation. The carbon CfD is designed to resemble ‘Contracts for Difference’ which are funded via a levy on consumer energy bills. Funding low-carbon policy via such a mechanism has already been proven to be regressive (Owen & Barrett, 2020). Funding future GGR policy similarly would further entrench inequality. Future policy costs should not be added to energy bills.

Although funding GGR technologies through income tax avoids excessive costs for low-income households, socializing costs may have the unintended consequence of blunting the price signal polluters face. Achieving full Pigouvian cost internalization (Pigou, 1920) and a degree of cost pass-through may be desirable to increase the marginal cost of production. In turn, this helps create an incentive to switch to cleaner

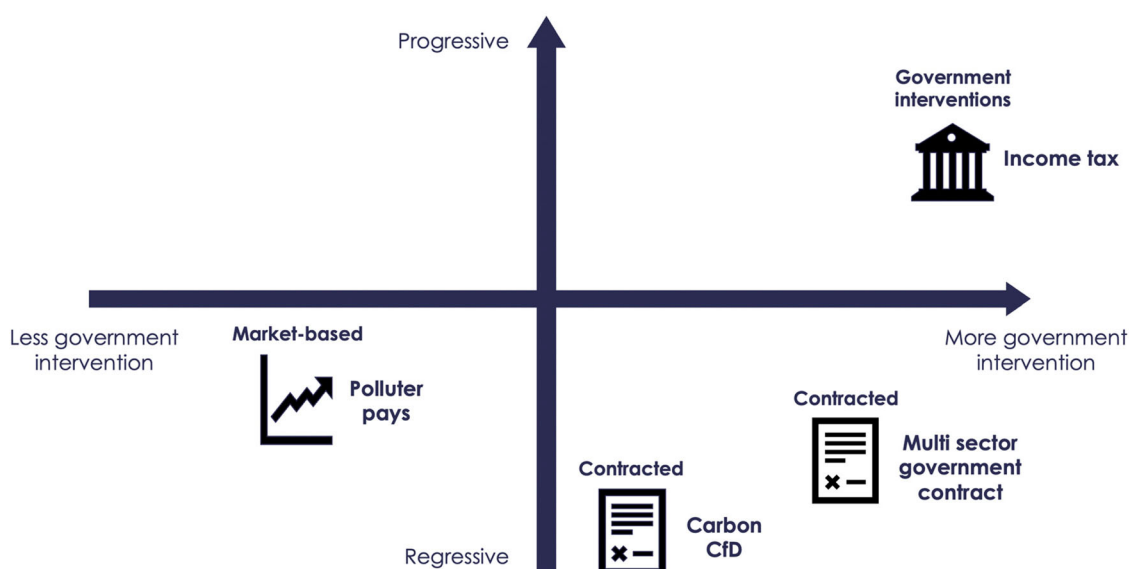


Figure 8. Impact summary of funding options.

inputs, adopt low-carbon technologies (Neuhoff & Ritz, 2019), or mobilize large-scale investments to achieve carbon neutrality in hard-to-abate sectors. Perhaps less recognized is that companies and investors need a guarantee that they can recover some incremental costs, by achieving higher sales prices for carbon-neutral products (Burke et al., 2021). In other words, a GGR policy framework that achieves full carbon cost pass-through may be needed to transform hard-to-abate sectors and enable them to direct investments towards low-carbon technology.

4.2. Sectoral implications and limitations

How the costs of BECCS and DACCS are apportioned between sectors is important if the costs are passed through to consumers via higher prices for goods and services. Across our three policy funding options that use a sector-based approach to cost allocation (see Figure 7),¹⁵ by 2050, the majority of costs are passed through to aviation, agriculture (food), and electricity supply. Here the distributional outcomes are determined by income elasticity of demand, differences across and within income groups (Steckel et al. 2021), and direct and indirect consumption patterns of household energy and food, rather than of transport. Oswald et al. (2020) find that globally, while heat and electricity elasticities are mostly below 1, transport is generally above 1. Passing on costs via transport could be more progressive as transportation has both a high elasticity and high emissions intensity. However, Mattioli et al. (2018, p. 226) demonstrate that low-income, high fuel spend households in the UK have a 'low response to fuel price increases' suggesting they choose to compromise spend on other items rather than give up car travel.

Funding GGR technologies via a levy on consumer bills (option 2) would be particularly regressive, as the low-demand elasticity suggests that this would result in lower energy consumption amongst the fuel poor. Funding option 3 may also have undesirable outcomes because the costs are passed through in the form of higher prices for all products that involve electricity in their provision. This is in a context where increased electrification is an important driver of decarbonization. Hence, increasing the cost of electricity inputs may slow down the production and uptake of cleaner alternatives (for example, heat pumps or electric cars) such that only wealthier households can afford to switch.

Under the polluter-pays mechanism, costs of BECCS and DACCS are apportioned based on residual emissions. By 2050, this means that aviation and the agriculture sector will be disproportionately affected as we show in Figures 6 and 7. But because the demand elasticities for food and aviation differ across households at different levels of income, the impacts are likely to be different between income deciles. As higher-income households have larger carbon footprints deriving from aviation than lower-income households, passing on costs of GGR technologies via the aviation sector has the potential to curb CO₂ emissions with minimal impacts on social welfare (Fouquet & O'Garra, 2020), as income elasticities decline with rising income level.

For food, the distributional impacts of higher prices are less clear cut. It is important to understand short- and long-term demand changes in response to changes in cost. Research for the Department for Environment, Food and Rural Affairs (Tiffin et al., 2011) suggests that for most foods, consumers buy products out of habit and continue to do so even when prices rise. For income decile 1, a polluter-pays funding option passes on 67% of total costs via agriculture. This reflects previous research on food taxes which suggests the tax burden falls disproportionately on households in the lowest socio-economic class because they tend to spend a larger proportion of their food expenditure on emission intensive foods (Kehlbacher et al., 2016). Even though higher food prices may not lead to short-run changes in demand, passing on costs this way is regressive, as several other studies have shown (De Irala-Estevéz et al., 2000; Tiffin & Arnoult, 2010; Turrell & Kavanagh, 2006).

5. Conclusion

There is strong evidence of the need to deploy GGR technologies for achieving net-zero emissions in the UK. While working to limit the worst impacts of climate change, it is crucial to ensure that costs of the required

¹⁵Policy funding option (4), income tax, is a sector-agnostic approach to cost allocation (see footnote 13).

technologies, including BECCS and DACCS, are distributed fairly across society. Given public support of BECCS and DACCS is low, choosing a just and fair funding model is a prerequisite to ensure public legitimacy of deploying and operating these technologies. This quantitative analysis of the potential distributional impacts of different ways of funding GGR technologies provides policymakers with evidence they can use when deliberating politically acceptable policy pathways.

Four policy funding options for GGR technologies – namely, BECCS and DACCS – were explored. Three resulted in low-income households paying disproportionately more towards the costs of GGR technologies where levying the costs entirely on the energy bill was the most regressive. Notably, this option most closely resembles current UK Government policy for funding subsidies for low-carbon generation. This demonstrates the risk of further entrenching inequality if GGRs are paid for in the same way. Whilst the overall distributional incidence is a typical phenomenon in the literature, the magnitude of, and the relative comparison between, the different policy options for funding GGR is novel. Here the paper's main contribution is to provide first numbers about the magnitude of different policy options on household income deciles to policymakers and the policy debate more broadly.

Looking at the sector implications of the different funding models, aviation emerged as an important point of intervention from a distributional perspective in the two funding options designed to distribute costs across different sectors (Figure 7, options 1 and 3). Higher-income households have larger aviation carbon footprints than lower-income households (see Figure A21 in the SI), meaning passing costs onto households via aviation alone could help fund GGR technologies while having minimal impacts on social welfare. However, the progressive effect of passing costs via aviation for options 1 and 3 is tempered by the inclusion of other sectors – such as land use – which represent a much higher proportion of spend for lower income households compared to aviation. The overall effect is that policy options 1 and 3 remain regressive, despite the inclusion of aviation.

Funding GGR technologies via income tax emerged as the only progressive way of apportioning associated costs across income deciles. As the benefits of GGR accrue to society as a whole, there is further argument that the costs should be shared across society in the fairest way possible. However, such an approach has the potential to blunt the price signal that polluters face. In reality, some pass-through cost may be desirable to adhere to equity principles under a polluter pays principle and to create an incentive to switch to cleaner inputs and adopt low-carbon technologies. While socializing the costs is not currently considered an attractive option by the UK Government, our analysis shows that it is possible to design progressive funding models for GGR technologies, should the political will exist.

As the UK looks to meet its ambition of deploying at least 5 MtCO₂yr⁻¹ of 'engineered'¹⁶ removals by 2030, there is an opportunity to develop a fair and enduring policy framework that can also serve as a template to other countries whose policy incentives for GGR technologies are less advanced. Both in the UK, and globally, a GGR policy framework that is fair and fosters high levels of public legitimacy will be more successful than one without.

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¹⁶As previously noted, the UK Government in its Net Zero Strategy considers DACCS, BECCS, wood in construction, biochar, and enhanced weathering as part of engineering-based removals.

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