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RESEARCH AND THEORY

Climate policy as social policy? A comprehensive assessment of the economic impact of climate action in the UK

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Abstract
Co-benefits are central to the case for climate action but are side-lined in many economic analyses. This paper presents an evaluation of three dimensions of the costs and benefits of climate change interventions in six urban regions of the UK. Findings indicate that meeting the UK's 2033–2037 climate targets could yield £164 billion in total benefits. Notably, only 13% of these benefits are financial, in contrast to the 79% of which are social benefits. These social benefits include improvements in public health, reduced traffic congestion, and increased thermal comfort in homes. These results underscore the need for economic evaluations to expand their scope and move beyond the narrow financial cost–benefit analysis that predominates. Moreover, the magnitude of the social benefits underscores the need for integrating social and climate challenges in policy-making. Concurrently, the results demonstrate the sensitivity of the social benefits of climate actions to the normative aspects of empirical analysis. Determining whether emissions reductions in the transport sector, for example, should be achieved through the deployment of electric cars, expansion of public transport, and/or increases in walking and cycling requires both technical analysis and value-based decision making. Ensuring that decision-making processes are deliberate and transparent in empirical analysis is therefore critical. We conclude by suggesting that institutions such as the UK Climate Change Committee and Scottish Climate Intelligence Service should take the opportunity to be more explicit in the normative decisions embedded in their empirical work to demonstrate best practice for the wider research community.

Keywords Climate change · Co-benefits · Urban climate action · Sixth Carbon Budget

Introduction

The multiple crises currently facing the world create a uniquely challenging moment for climate policymaking. Coal powerplants that were due for retirement, for example, are being maintained to improve energy security, and responses to COVID-19 have led to reduced climate action in some parts of the world (Romanello et al. 2022).

At the same time, opportunities to intervene across multiple challenges are being revealed. Ukrainian self-determination, European energy security and global action on climate change, for example, are jointly supported by actions to reduce energy demand across the EU (Creutzig 2022). Understanding the wider impacts of climate policies may therefore be uniquely important during this period of overlaps and intersecting crises known as the policrisis (Lawrence et al. 2024).

So-called "co-benefits" have remained largely absent from economic analyses of climate change despite compelling arguments being made as early as the IPCC's second assessment in 1996 that these wider impacts of climate mitigation are critical to the case for action. A number of reasons account for the limited role of co-benefits in the economic modelling of climate action. A lack of data and the uncertain, context-specific and contingent nature of many co-benefits has led to challenges drawing conclusions across literature (Gouldson et al. 2018). Controversy has surrounded the appropriate means of integrating the

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impacts of climate measures that affect people (health, wellbeing, heritage, culture), affect nature (biodiversity, ecological integrity), and are financial (Köberle et al. 2021). Imperfect means of measuring and operationalising co-benefits that are qualitative in nature and a high degree of variability of co-benefits between contexts underpin these challenges. This has led to significant difficulties replicating studies and generalising findings in ways that have policy relevance (Sudmant et al. 2024).

Several authors have argued that the case for a more comprehensive assessment of the costs and benefits of climate action is of limited value (Köberle et al. 2021; Weitzman 2009). Tipping points and the consequences of insufficient action underpin the case for action, implying that a more nuanced analysis is a second-order consideration (Piontek et al. 2021; Weitzman 2009). The uncertainty added by including a broader assessment of the net case for action, according to this perspective, can act to "obscure rather than clarify" policy options (Köberle et al. 2021, p. 1036).

Competing with these claims are literature highlighting the unique importance of co-benefits to a more robust response to climate change. Transformative opportunities have been found from combined approaches to climate change, energy, cost-of-living, and health crises (Romanello et al. 2022, 2023). Motivation to achieve co-benefits can overcome ideological barriers to supporting climate action, suggesting that co-benefits are key to the political case for climate action (Bain et al. 2016; Bergquist et al. 2020). The degree to which climate actions make the poorest in society better or worse off is significantly determined by the kinds of co-benefits and co-costs climate actions generate, making an assessment of co-benefits important to a Just Transition (Colenbrander et al. 2017; Rauner et al. 2020; Emden et al. 2024; Vandyck et al. 2020). Furthermore, unwarranted simplification and omission of complexities related to the quantification of climate action costs and benefits have been found as key driver of the macroeconomic losses from climate action (Köberle et al. 2021).

In the UK, the wider costs and benefits of climate action have been a steadily emerging area of focus. The co-benefits of climate action in the UK that are highlighted by the Climate Change Committee (CCC) (a non-departmental public body tasked with advising the government on climate action) include improvements in health, air quality, energy access and security, job generation and economic development (CCC 2019). Analysis from Forster et al. (2013) of co-benefits considered by the CCC found that the net-benefits of climate action could be £85 billion and recent analysis by Milner et al. (2023) found that the health benefits of climate actions in the CCC's pathways could exceed 2.5 million life years through 2050. Each of these papers is explored in more detail in the discussion section.

This paper adds to existing literature and discussion in three ways. First, analysis uses the most up-to-date UK government guidance for the measurement of the wider impacts of climate actions, including from the UK Green Book (HM Treasury 2020), Transport Analysis Guidance (TAG 2021), and the UK Climate Change Committee (CCC 2022). Utilizing these methods grounds our analysis in the existing approaches of UK government, which allows the results of this analysis to be relevant to ongoing policy development. In particular, comparison of the co-benefits from different interventions and in different urban areas is relevant to the government's place-based approaches to climate action, which currently include Department for Energy Security and Net Zero's net zero hubs and Local Net Zero Accelerator pilots, and the development of local area energy plans (LAEPs) and Local Heat and Energy Efficiency Strategies (LHEES) in Scotland.

Second, this analysis includes three dimensions of climate impacts, allowing for a comparison of the relative case for action in a more comprehensive manner than has previously been published in the UK. The financial case for action in this analysis includes the direct costs and benefits, those relating to investment, operational costs and energy costs/savings. The social case for action is assessed by quantifying and monetizing a range of social benefits, including excess cold, indoor air quality, physical activity, traffic accidents, congestion, noise and the benefits of warmer homes (home comfort). The carbon case for action monetises the value of climate actions using the marginal abatement cost needed for the UK to meet its 2050 net-zero target. In this way the 'carbon case' for action captures the value of avoiding more costly future abatement.

Third, analysis explores how value-based decisions shape the co-benefits of climate interventions. Comparing results of this analysis with similar studies underscores how choices made during the modelling process—such as which interventions should be prioritised—reflect underlying normative frameworks. In the discussion and conclusion, we discuss how surfacing and making explicit these normative aspects of empirical climate analysis may be increasingly important as climate action accelerates and as climate interventions expand into realms that are more socially and politically sensitive.

Methodology and context

A version of the so-called 'mini Stern' methodology for climate action that has been applied in a number of local authorities to the UK (Gouldson et al. 2015; Sudmant et al. 2017; Williamson et al. 2020) and in a number of international contexts (Colenbrander et al. 2016; Papargyropoulou et al. 2015; A. Sudmant et al. 2016). Named after the Stern

Review (Stern 2007), a landmark report on the economics of climate change in the UK, 'Mini Stern' analyses consider the economic case for climate action within a defined city or region using techno-economic models of low and zero carbon climate action interventions. In this analysis ~ 750 measures are applied in a scenario analysis designed to meet the equivalent of the UK's 6th Carbon Budget for each of 6 urban regions. Using this approach, the costs and benefits of climate action are considered at the city region level. The full details of the methodology can be found in Appendix 1.

Analysis covers six urban regions which were selected to capture the diversity of urban contexts in the UK, including urban regions from each of the four nations (Scotland, Northern Ireland, Wales and England) and from cities with both relatively larger and smaller industrial sectors. The six urban regions are Glasgow, Belfast, Swansea Bay, Liverpool, Greater Manchester, and Cambridgeshire and Peterborough. London was not included in this analysis due to the transport model in our analysis not being capable of including some aspects of the London transport network. Analysis focused on the buildings and transport sectors where more than 80% of emissions from these cities are produced.

The UK's 6th Carbon Budget sets out the level of emissions the UK can emit between 2033 and 2037. Since the UK's emission is expected to fall in a consistent year-on-year fashion, the 6th Carbon Budget is often described as a reduction in GHG emissions of 78% in 2035 on 1990 levels. To align with the 6th Carbon Budget, scenarios in this analysis achieve 78% reductions in the GHG emissions that come from buildings and transport in each urban region (Fig. 1).

Local governments in the UK have responsibility over the provision of services and key powers over planning and development. The primary responsibility for climate action, however, is generally understood to lie with national

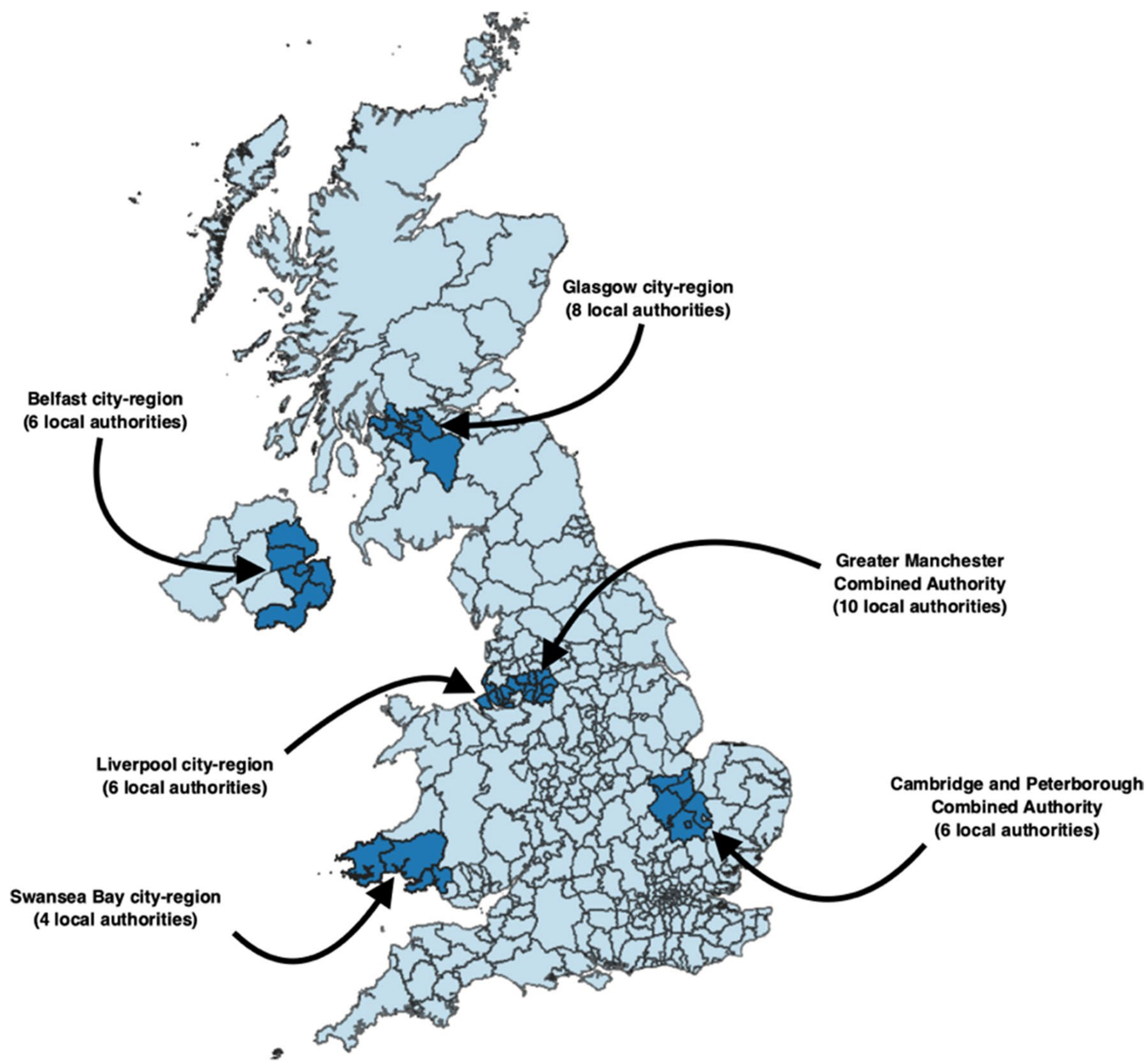


Fig. 1 Urban regions included in the analysis

government, which holds powers over taxation and environmental legislation and regulation, and which, unlike local government, is legally responsible for achieving the country's carbon budgets.

Applying best-practice UK government methods and datasets, including from the Transport Analysis Guidance (TAG) and the UK Green Book (a guide for the evaluation of government programs plans and policies), we conducted a cost–benefit analysis of interventions (individually and across scenarios of actions) to assess the financial case for actions. To assess the social case for action we monetized the impact of these actions for a range of social benefits, including excess cold, indoor air quality, physical activity, traffic accidents, congestion, noise and warmer homes (home comfort). To assess the carbon case for action we used the UK Government's Greenhouse Gas Emissions Value to estimate the carbon benefit of these interventions. The UK Government's Greenhouse Gas Emissions Value is a 'target-consistent' estimate of the carbon price consistent with the UK reaching its climate targets based on estimates of the marginal-abatement cost curve.

A high-level presentation of the approach of the analysis is found in Fig. 2, using the transport sector as an example. The approach for avoiding double-counting of benefits follows guidance from the UK Green Book (HM Treasury 2020). There are some limitations to this approach. For example, analysis did not consider how the health benefits from exercise change when air quality is improved. In order to make the paper more succinct, detailed information on the sources of information that underpin the analysis, key assumptions and the flow-charts for the remaining sectors are found in Appendix 1.

Global benefits of climate action, including several that are foundational to the global case for action, are not assessed by this analysis. These benefits include the value of impacts avoided from reduced agriculture productivity (Ortiz-Bobea et al. 2021), loss of biodiversity (Pires et al. 2018), heat stress (Santamouris 2020; Vicedo-Cabrera et al. 2021), and desertification (Huang et al. 2020). In addition, several strategically important benefits of climate action are not assessed by this analysis. For example, the strengthening of zero carbon supply chains and increasing the UK's resilience to extreme climate events, which would both have widespread social and economic benefits, are beyond the scope of analysis in this study.

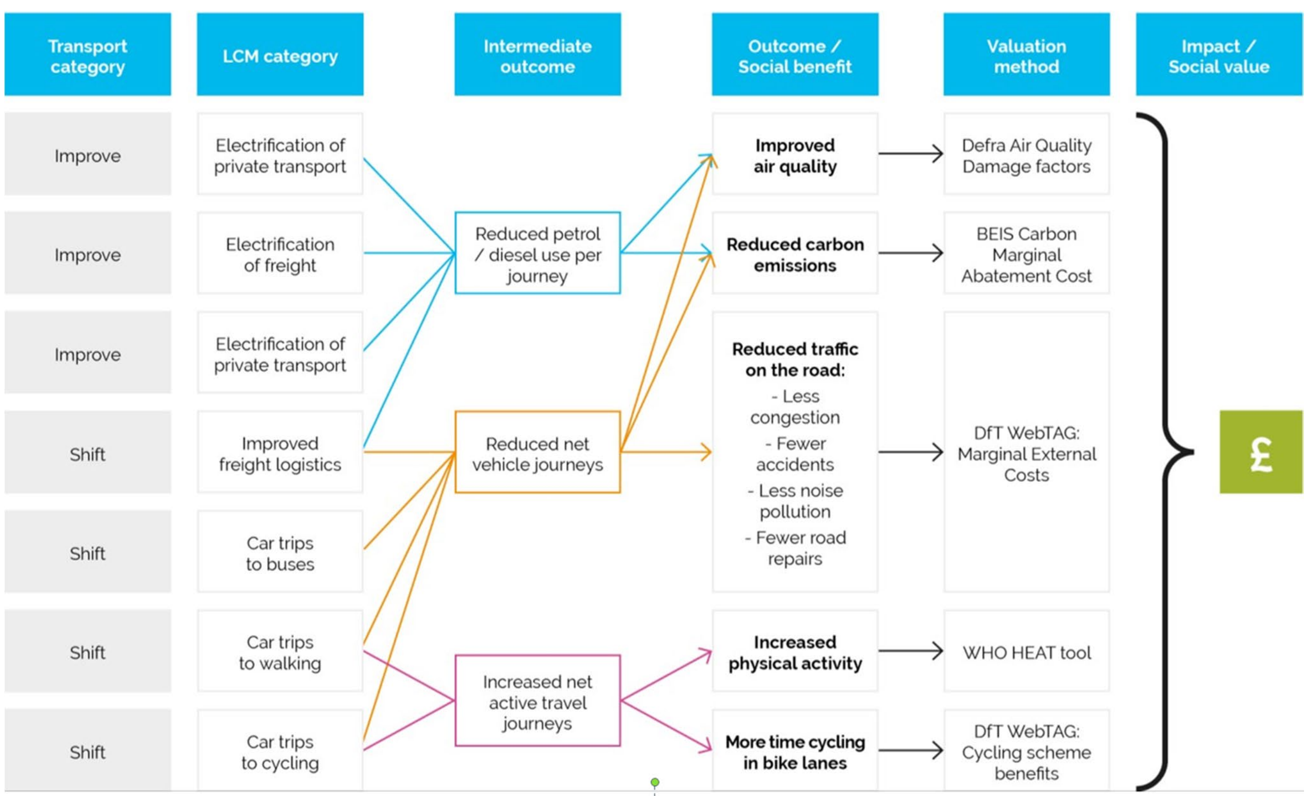


Fig. 2 A high-level representation of the methodological approach applied to calculate the value of co-benefits in the transport sector

Results

In the following section, we consider results across urban regions. Next, we compare findings between urban regions to understand how the scale and makeup of the case for climate action differs between the places. Finally, we explore how different measures lead to different costs and benefits of action.

The case for action

We found that a program of action consistent with meeting the UK's 6th carbon budget in the 6 urban regions of this analysis would generate £179 billion in total benefits and £164 billion in net benefits. Seventy-nine percent of all benefits are in the form of social benefits, while 8% come from the carbon benefits of action (the value of avoided future mitigation) and 13% from net financial savings (primarily in the form of energy savings). The financial case for action, including only the market costs and benefits of actions, is significantly more modest: £8.7 billion with capital costs of £14.5 billion and savings from avoided operational costs and energy usage of £23.2 billion. The net financial case includes all the financial costs and benefits of climate actions. The total benefit case includes all of the costs and benefits of climate actions (Fig. 3).

Climate action benefits by urban region and sub-benefit type

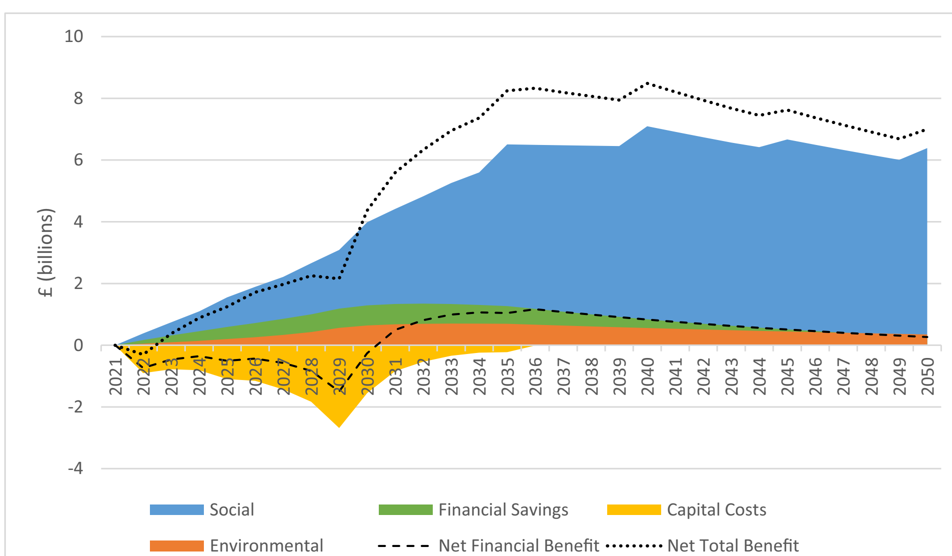
Figure 4 shows the non-market benefits of climate actions. The social benefits and carbon benefits are shown in Fig. 4 by urban region on a per capita basis with differences between city regions reflecting different levels of opportunity for the implementation low and zero carbon measures. The social benefits of climate action are significantly greater than carbon benefits within and between cities—across cities the social benefits of climate action are £16,552 per capita, while the carbon benefits are £1,586. The scale of benefits also differs significantly between urban regions. Carbon benefits on a per capita basis are largest in Glasgow (£2,119 per capita) and smallest in Belfast (£1,233 per capita). Similarly, social benefits are largest in Glasgow (£23,039 per capita through 2050) and smallest in Belfast (£8,404 per capita through 2050). Congestion improvements are the largest source of benefits across urban regions, with physical activity being the next greatest category. Congestion improvements are generated by climate measures that shift travel from private vehicles to buses, walking or cycling. The benefits of congestion and physical activity are 86% of the total social benefits of climate action.

Figure 5 shows the market benefits of climate actions between urban regions via the net financial benefits of GHG mitigation on a per capita basis. Mean per capita net financial benefits across urban regions are £1,011 from 2022 to 2050, ranging from £326 in Glasgow to £1,645 in Belfast. Interventions in the transport sector are the most cost-effective in all urban regions, with the domestic and non-domestic sectors generating net financial returns in some urban regions and net costs in others. The financial savings are primarily in the form of energy expenditure savings.

Climate action benefits by intervention

Figures 6 and 7 show the cost per tonne of GHG savings if social, carbon or financial benefits alone were used to value mitigation measures. Both figures present the same

Fig. 3 Discounted annual benefits of climate actions by benefit type, and capital costs



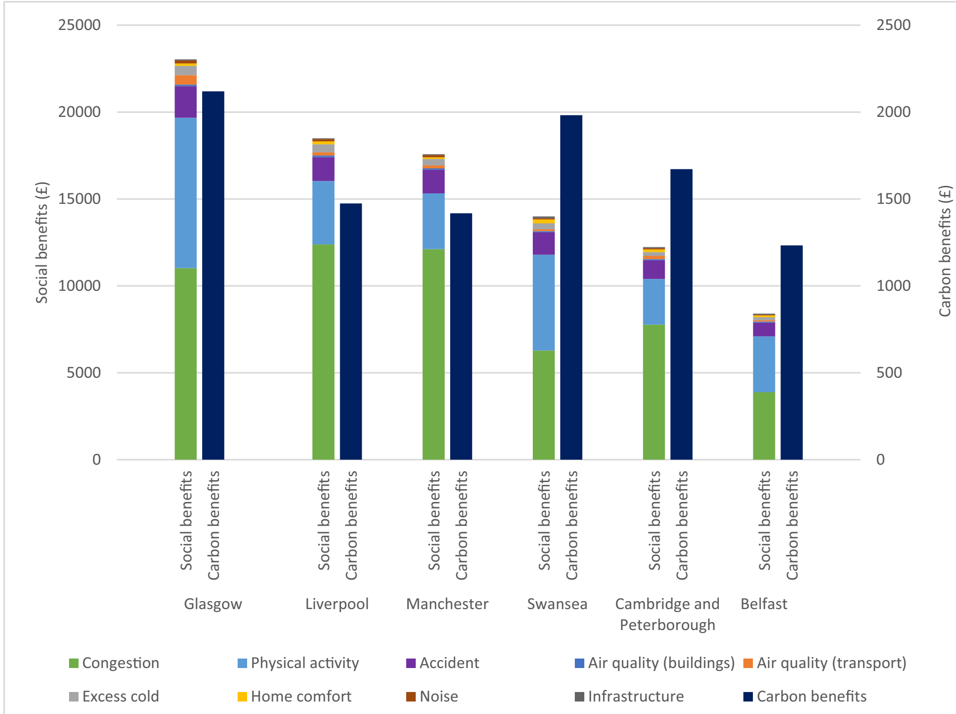


Fig. 4 Per capita social benefits by urban region

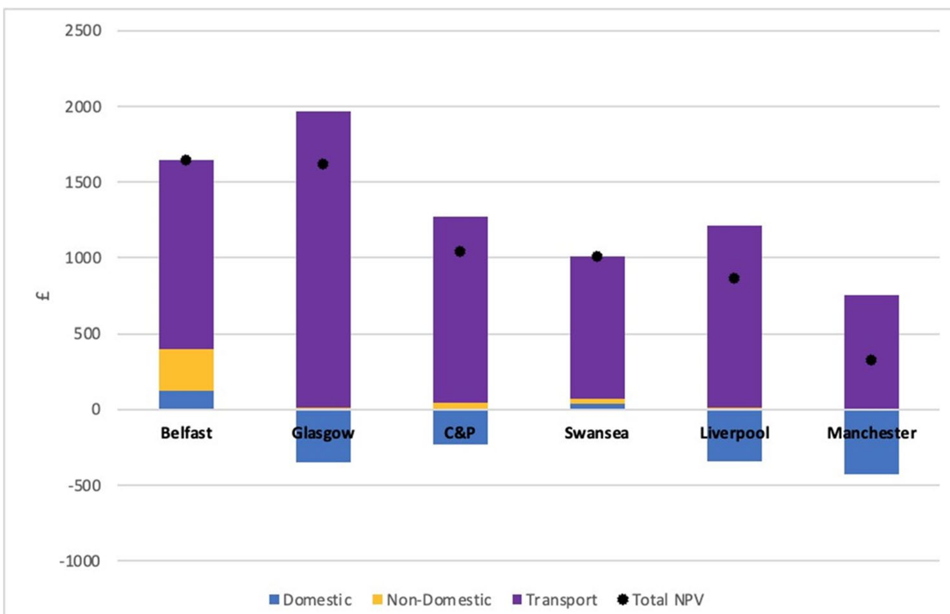


Fig. 5 Per capita net-present value of financial case for action on a per capita basis

data at different resolutions. Coloured regions indicate the locations of the largest number of individual measures of specific measure-type clusters. Measures are ranked by their average social benefit per tonne of GHG emissions saved, with measures shifting people out of private cars delivering social benefits that are too large to capture in Fig. 6.

In the majority of cases (seven out of thirteen cases) the financial benefits of actions—the net energy savings and operating cost savings from measures—are larger than the social and carbon benefits of measures. In four cases the social benefits of climate action are larger than the carbon and financial benefits of action and in only two cases the carbon benefits of action are larger than the social and financial benefits of action. These results show that while the largest aggregate benefits from climate action come from the social benefits of action, for a majority of interventions

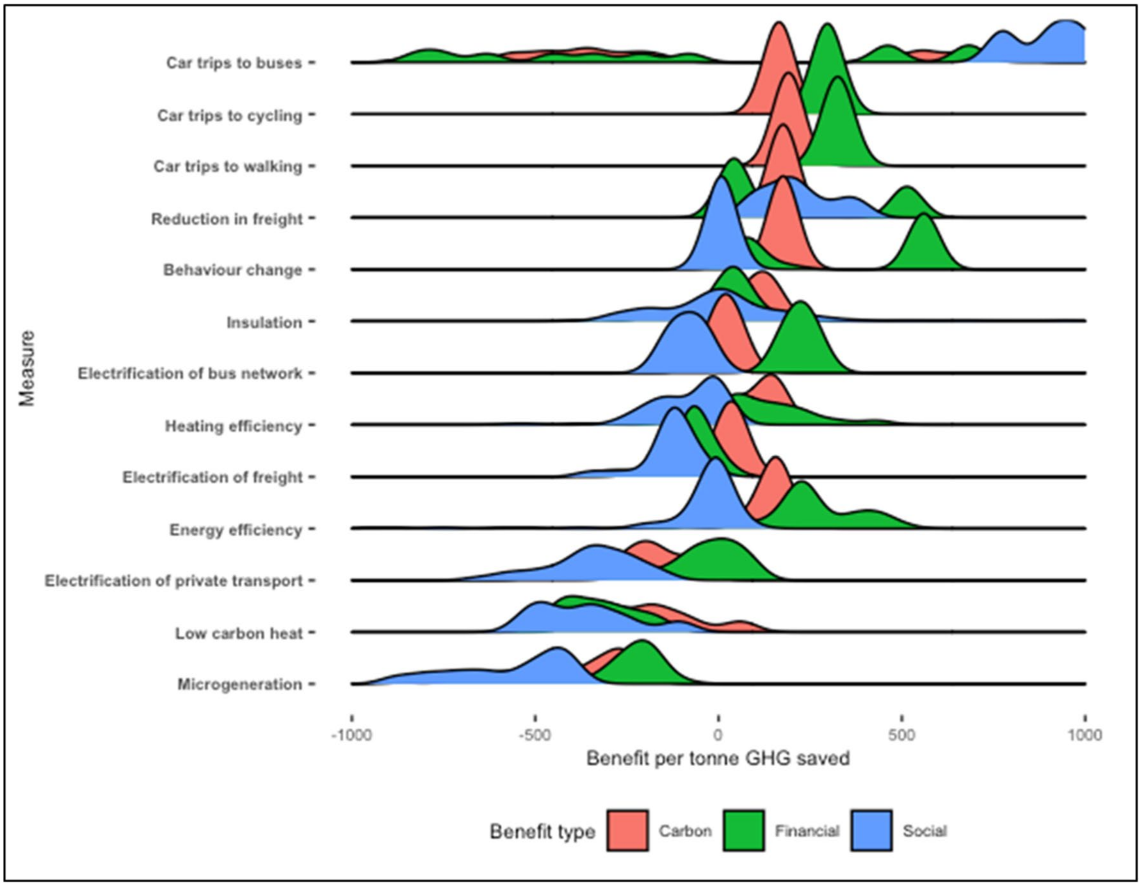


Fig. 6 The density of social, financial and carbon benefits of climate action between -1000 and + 1000 £ per tonne GHG savings. The same data is shown in Fig. 7 at a different resolution

the financial case for action (primarily from energy savings) provides a more compelling case for action.

Figures 6 and 7 show where the majority of individual measures cluster but do not take into account the scale of GHG savings from individual measures. In Fig. 8, marginal abatement cost curves rank measures from most to least cost effective in order to explore the extent to which different kinds of benefits effect the scale of cost effective (net benefit generating) climate action.

A significant literature explores the limitations of marginal abatement cost curves, including around transaction and policy costs, the effect of interactions, and unintended consequences, see Vogt-Schilb & Hallegatte (2014) for further discussion. Acknowledging these limitations, marginal abatement cost curves (MACC) are used here to provide a high-level illustration of the relative scale of interventions and their costs, in line with literature that used MACC curves for the same illustrative purposes (Ibrahim & Kennedy 2016; A. H. Sudmant et al. 2017).

Figures 6 and 7 demonstrate that the concentration of social benefits in a small number of measures leads to a smaller volume of emissions that can be mitigated at a negative cost if assessment only considers the social benefits of climate action (as well as the direct costs of interventions). The total volume of emissions that can be mitigated at a negative cost is 74.3Mt CO2e when only social benefits are considered, but 107Mt CO2e (44% more) when financial benefits are considered and 128Mt (73% more) when carbon benefits are considered. Figure 7 thus shows that the carbon benefit of climate actions, despite contributing a relatively small share of total climate benefits (Fig. 2) and being less important than financial or social value for specific interventions (Figs. 5 and 6), plays an important role in supporting the business case across a large set of interventions. Consequently, the carbon benefit of climate action leads to the largest volume of negative cost GHG savings.

To explore the way different dimensions affect the case of climate actions, Fig. 9 shows low and zero carbon measures coloured by measure type on a ternary plot. A ternary plot shows the relative share of the total value of each measure contributed by each of the three dimensions. Three findings are notable. First, while social benefits are very large for measures that shift travel from private cars to non-motorised and public transport options, the financial benefits are also

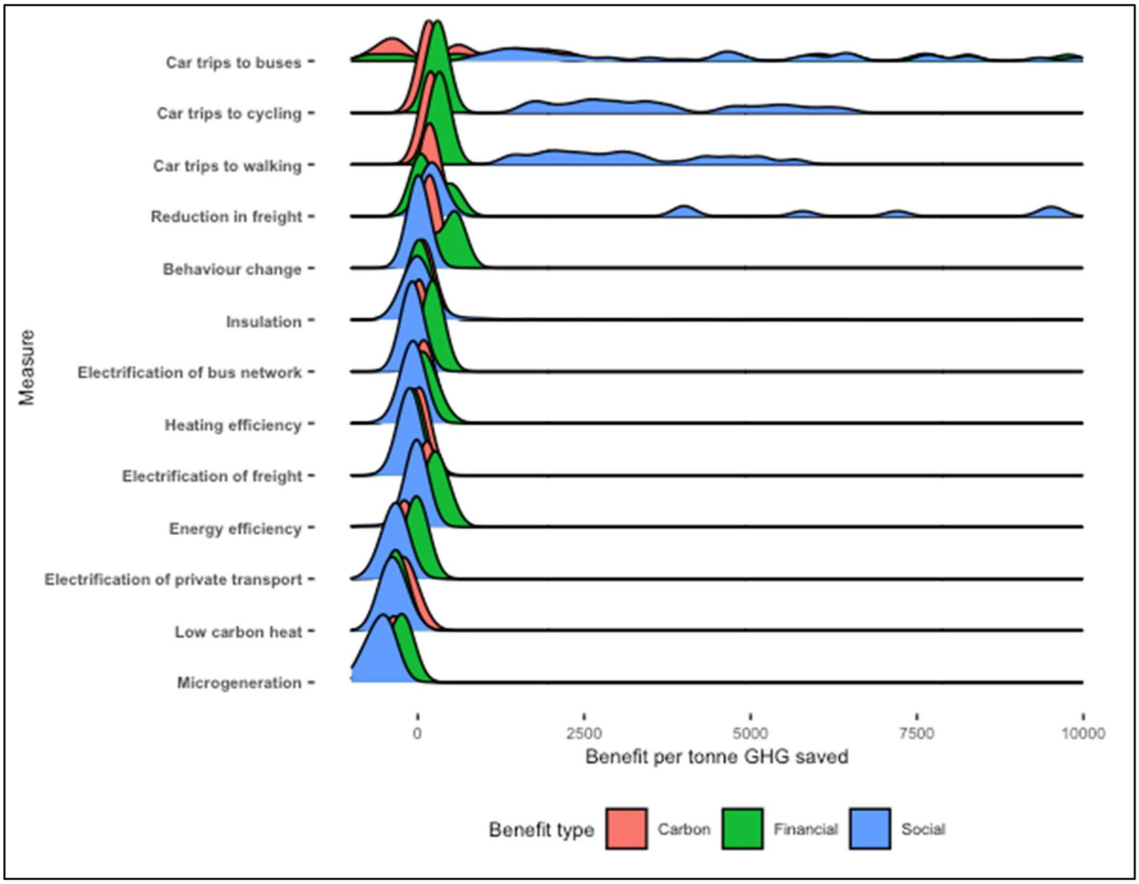


Fig. 7 The density of social, financial and carbon benefits of climate action between -1000 and + 10,000 £ per tonne GHG savings. The same data is shown in Fig. 6 at a different resolution

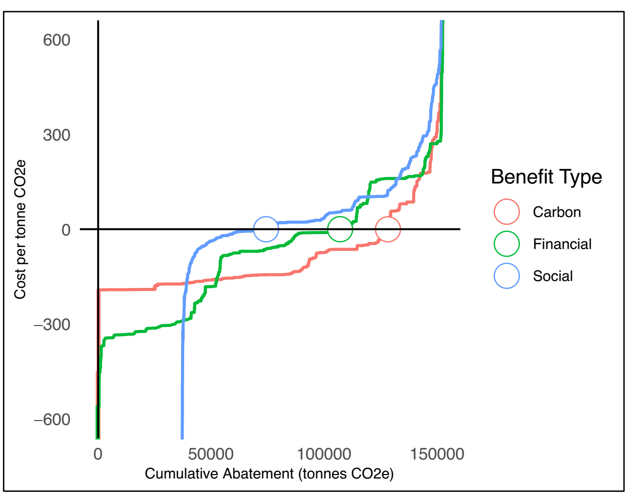


Fig. 8 Marginal abatement cost curves developed from the social, carbon and financial costs of climate action

very large (Fig. 6), suggesting that developing a case for implementing these measures may not strictly depend on the development of the social case for action. Second, specific types of measures are shown to depend on a carbon or financial case for action. Electrification of freight and transport depend on the financial case for action while heating and energy efficiency measures depend on the carbon case for action. Finally, few measures are found near the centre of the diagram, suggesting that it is combinations of two of the financial, social and carbon cases for action that are important to the case for action for most measures (Table 1).

Comparing the financial, social, and carbon cases for climate action

The financial case for climate action

The financial benefits of implementing low-carbon measures are found to more than offset the capital and operating costs of action. Across all sectors and urban regions—representing 13% of the UK's population—the net cost of achieving mitigation commensurate with meeting the sixth carbon budget, is -£8.7 billion with capital costs of £14.5 billion and savings from avoided operational costs of £23.2 billion. Financial

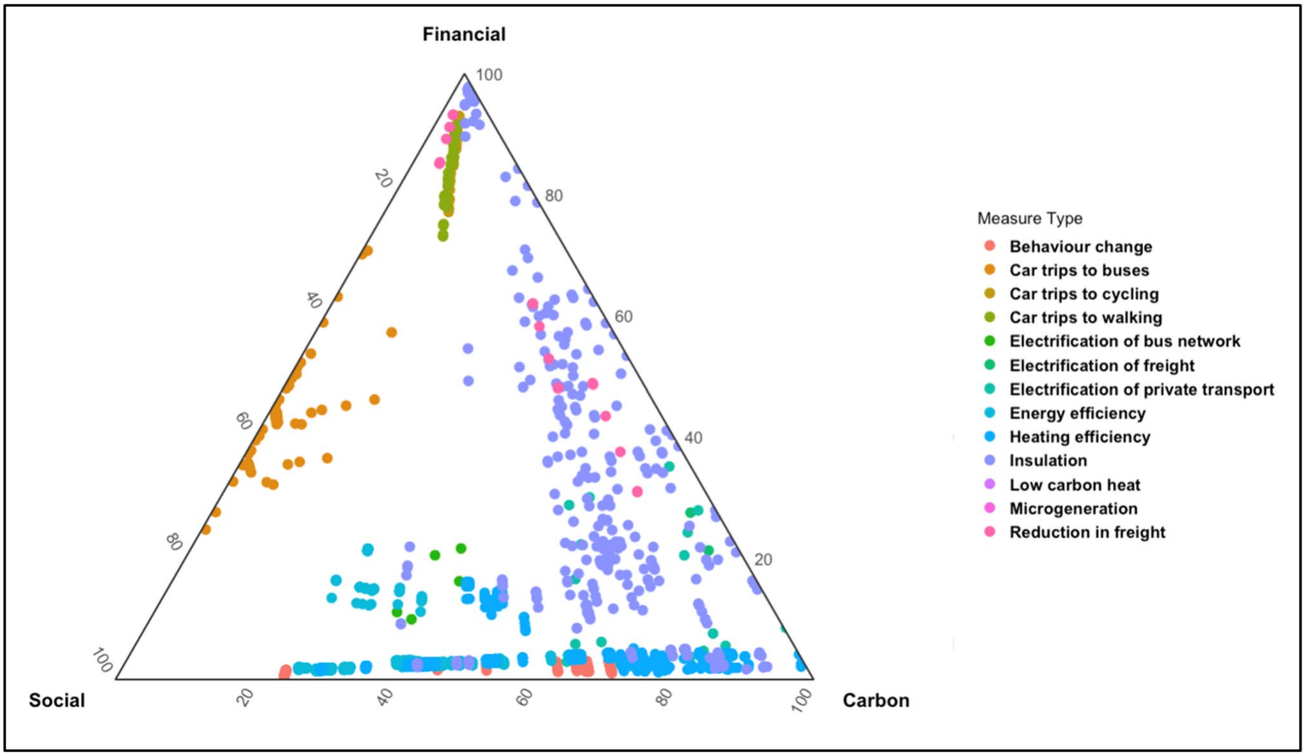


Fig. 9 The relative social, financial and carbon case for measures by type. Each axis captures the share of total benefits from a benefit type

Table 1 Social costs and benefits of climate action included in analysis by type

Social Co-benefit	Definition
Congestion	The value of reduced time spent traveling and road repairs from reduced numbers of vehicles on roads
Infrastructure	The value of repairs avoided when infrastructure (in this case solely roads) are used less frequently
Air quality – transport	The value of public health benefits from reduced air pollution from transport
Air quality – buildings	The value of public health benefits from reduced air pollution from buildings
Physical activity	The value of health benefits from increased walking and cycling
Excess cold	The value of reducing visits to hospital attributable to insufficient heating
Home comfort	The additional comfort to households when higher efficiency of appliances allows those appliances to be used more frequently
Accidents avoided	The value of reduced vehicle repairs and lives lost from vehicle accidents
Noise	The value to public health and worker productivity from reduced noise

savings are found to constitute 13% of the total benefits of climate actions and are the largest source of benefit for seven of the thirteen types of measures assessed.

These figures align with literature assessing urban climate action in the UK and other wealthy nations. Williamson et al. (2020) and Gouldson et al. (2020), for example, both found that GHG emissions could be reduced more than 40% in ways that generate financial returns in cities in the UK. Analyses for New York (New York State Climate Action Council 2022), San Antonio (City of San Antonio Office of Sustainability 2021) and Toronto (Ibrahim and Kennedy 2016) similarly found significant potential for cost-negative climate action. These findings present a more optimistic impression of the cost of climate action, however, than current government assessments.

While the CCC has been cautious about placing a definitive figure on the net cost of action, the 6th carbon budget concludes GDP could be increased by 2% by 2035 with an annual cost of 0.6% of GDP in the early 2030s falling to 0.5% of GDP by 2050. These figures for the net cost of action are smaller than previous CCC analysis that expected costs to rise to 2% of GDP by 2050. The increase in GDP, and reduction in net annual costs, are primarily the result of reduced expenditure on energy (CCC 2022). Research from the Office of Budgetary Responsibility (OBR 2021) found the total costs of mitigation in the UK to be £1.4 trillion, with £1.1 trillion being offset through financial savings.

The differences between the estimates from the CCC and OBR and the results of this analysis can be attributed to differences in the scope of analysis. Where analysis here is limited to the buildings and transport sectors, the CCC and OBR analysis cover all sectors of the economy, including abatement challenges in sectors such as land-use and industry. In addition, analysis here achieves the 6th carbon budget but not the further reductions necessary to meet net-zero. These 'final' emissions are generally understood to be the most costly to abate, although CCC has noted that literature frequently has been too conservative, with innovation and market forces resulting in lower costs than previously projected (CCC 2022).

The social case for climate action

The social benefits of achieving the 6th carbon budget in the city regions in this analysis is £142 billion and 79% of the total benefits of climate action assessed by this analysis. These figures are larger than estimates in existing literature. Similarities in effect sizes at the level of individual interventions suggest the difference between this study and other literature are largely attributable to the scale at which climate measures were implemented. In the following, we specify the methodological differences between this study and similar literature. In the conclusion of this section and continued in Sect. 5.2, we consider what it means for empirical analysis of co-benefits that methodological choices can underpin significant differences in our understanding of the case for climate action.

Previous work completed for the UK Climate Change Committee by Ricardo Economics (Forster et al. 2013), modelled the medium abatement potential of the fourth carbon budget. Across complimentary sectors in analysis here and in Forster et al. (2013), the largest benefits originated from reductions in congestion and the second-largest benefits from increased physical activity. The scale of benefits, however, is significantly different between studies. While Forster et al. (2013) found annual benefits across transport and building sectors worth approximately £80 per capita, this analysis found benefits of £552 per capita.

A similar divergence is found between our results and those in Milner (2023). Milner et al. (2023) model mortality improvements across England and Wales (2021–2050) measured in cumulative life-years gained from the CCC's Balanced Pathway and Widespread Engagement pathway. Assessing air quality improvements from the transport sector, this analysis estimated mean annual per capita benefits of £7.43 from PM2.5 and PM10 reductions. This value is significantly larger than the £60,000 per life-year gained in Milner et al. (2023), which equates to £1.83 per capita. Total co-benefits arising from increased physical activity scaled to the level of the UK (to enable comparison) are £225 billion from this study and £17 billion in Milner et al (2023) if £60,000 per life-year gained is applied.

Per capita health benefits are therefore approximately 4–13 × larger in this study than in existing research. Differences in effect sizes from interventions, however, are dramatically smaller. Analysis here, for example, found health benefits of approximately 14 pence per km, just less than double the £0.08 per km implied (at £60,000 per life-year gained) by Milner et al. (2023) and considerably less than the £0.80—£1.10 per kilometre cycled in direct health benefits found in other literature (eg Davis 2014). Similarly, congestion benefits in this analysis are approximately 7 pence per vehicle-kilometre avoided, smaller than comparable literature (Parry and Ian n.d.) and the 12.4 pence per vehicle-kilometre (in 2012 prices) in Forster et al. (2013).

Differences in the scale of social benefits from climate action between this study and wider literature are therefore primarily driven by dramatic differences in the scale of deployment of certain interventions rather than valuation methodologies. Daily mean active travel increases by 2.84 km per person by 2037 in this analysis, but only 0.34 km pp by 2050 in Milner et al. (2023). Forster et al. (2013) models a reduction in vkms of 1.7% through 2050 while analysis here models a reduction of 13% of vkms.

Whether the scale of non-motorised measures employed in this analysis is realistic is in part a technical question to be assessed based on parameters found in literature and the characteristics of the area being assessed. In this context, we note that co-benefits in this analysis are capped according to HEAT methodology, fall below HEAT thresholds and are aligned with recommendations from other literature (eg Brand et al. 2021; Jarrett et al. 2012). Even at the level of implementation in this analysis, cycling kilometres per capita would be significantly below the levels in Denmark and the Netherlands today (Mueller et al. 2018) and comparable to the rates achieved in Paris over the last 2 years (Meeks 2023). Whether achieving GHG reductions targets without rapid and large-scale reductions in car use has also been questioned, including from literature focusing on the UK (Winkler et al. 2023).

Insofar as assessing the realism of scenarios is a technical question, however, it is also a question that is deeply and fundamentally normative. Whether a future transport system should focus on non-motorised mobility, enabled by 15-min cities, mixed development and high-quality public transport, or have a relatively larger focus on zero carbon private transport options, is in part determined by the perspectives of the team engaging in the modelling exercise. The same attitudes, perceptions, political views, habits and aspects of the social environment that determine whether an individual is willing to cycle (Willis et al. 2015), are undoubtedly involved when a modelling team considers whether individuals are willing to cycle. The scale and nature of co-benefits from climate action are therefore significantly affected by value-based decisions that are frequently embedded deep in the appendices of empirical modelling exercises. In Sect. 5.2 and the Conclusion, we consider what this means for empirical work on the co-benefits of climate action and the modelling of pathways to net zero.

The carbon case for climate action

The discounted total value of carbon saved from mitigation in this analysis is £13.6 billion across urban regions. This amount represents 8% of the total value of the benefits of climate actions.

Carbon values are used by the UK government for valuing changes in GHG emissions resulting from policy interventions. Carbon values represent monetary value placed on dioxide equivalent and differs from the 'price of carbon' which represents the observed price of carbon offsets in a market (for example the UK or EU Emissions Trading Schemes). These values also differ from the social cost of carbon, a measure of the long-term damage caused by GHG emissions. Since 2009, the UK has applied a 'target consistent' approach to estimate the value of each tonne of carbon whereby the carbon value is calculated as the marginal abatement cost of meeting GHG targets. The carbon cost is therefore a measure that is specific to the UK's national context, both in terms of its GHG emissions and opportunities for mitigation.

Since the value of abatement will be the same irrespective of the source of savings (i.e. the sector or measure), the benefit of using carbon values concerns how the carbon value changes the cost/benefit analysis of a program or policy. Results here show that despite being a relatively smaller component of the cost/benefit calculation across all interventions and urban regions, the carbon value plays a critical role in the domestic and commercial sectors. Indeed, of the three dimensions of benefits from climate actions, the carbon value of action achieved the largest negative cost volume of emissions savings from actions (Fig. 7).

Towards a comprehensive approach to climate action

The importance of non-financial benefits for advancing climate action

Of the total benefit of climate action in the urban regions in this analysis, 13% comes from financial savings, a share that is likely overstated due to various global benefits of climate action, including to agriculture productivity (Ortiz-Bobea et al. 2021) and biodiversity (Pires et al. 2018), not being considered. The financial case for climate action, however, has been gaining substantial political and academic traction.

Even before the recent rise in energy prices, a growing body of literature presented the transition to a net-zero society as a financial opportunity. Climate policies can correct market failures such as those associated with fossil fuel subsidies (Monasterolo & Raberto 2019), and support innovation, productivity, and long-term economic growth (Stern 2022). Recent energy-economy analyses have found financial savings in the trillions of USD from a shift to green technologies (Jaxa-Rozen & Trutnevyte 2021; Shiraki & Sugiyama 2020; Victoria et al. 2021; Way et al. 2022).

These developments, and growing urgency to avoid tipping points in the earth's climate raise a reasonable question about the value of assessments of the case for climate action. Analysis here supports other literature in this field by suggesting that a better understanding of climate action's non-market benefits may have two key roles.

Firstly, even as the aggregate financial case for climate action is compelling, the wider benefits of action are important to the case for specific interventions (Ürge-Vorsatz et al. 2014; Grubb et al. 2022). Financial and non-financial costs of action are frequently concentrated for particular subsets of the population, in particular geographies, for particular levels or departments of government, or for particular kinds of actors; for example, owners of homes but not renters (Green and Gambhir 2019). These costs emerge from the need to reskill millions of workers (Bowen and Kuralbayeva 2015; Emden et al. 2024), the burden on the financial system from stranded assets (Mercure et al. 2018), the need for mobilising and redirecting billions of investment capital (Giglio et al. 2021) and the challenge of unlocking social and economic systems tied to fossil fuels (Ivanova et al. 2018). Many of these costs are financial, but the costs of an unjust transition are also to public health and to the social and cultural fabric of communities (Beatty & Fothergill 1996). In analysis here, measures to implement heat pumps in domestic homes are in many cases only cost-effective when social or carbon benefits are considered. Similarly, measures to improve insulation in commercial buildings and to expand public transport systems generate negative or negligible returns in the absence of consideration of carbon and social benefits.

Secondly, the wider benefits of climate actions may play an important role making the social and political case for action (Bain et al. 2016; Bergquist et al. 2020). Literature has found that 20–40% of urban GHG emissions are mitigable in ways that generate financial returns, but deeper and faster reductions that align with global carbon budgets require significant loss-making financial investment (Colenbrander et al. 2016, 2017; Gouldson et al. 2015; A. Sudmant et al. 2016; Williamson et al. 2020). This research suggests that while a transition of the energy-system as a whole may generate net financial returns (Jaxa-Rozen & Trutnevyte 2021; Shiraki & Sugiyama 2020; Victoria et al. 2021; Way et al. 2022), urban areas may concentrate legacy capital investments that are costly to replace or retrofit for a zero carbon future, emphasising the importance of understanding the non-market benefits of action. Financial benefits are the largest source of benefit for seven of the thirteen types of measures assessed in this analysis. However, the social benefits of climate action generate the largest aggregate benefits and the carbon benefits of action generate the largest volume of GHG emissions reductions that have a negative cost, generating a more comprehensive case for action.

The place-specificity of co-benefits and the normative aspects of co-benefit analysis

An understanding of the wider costs and benefits of climate action provides a means of engaging with the full scope of the impact on people's lives from the transition to a net-zero society. Climate actions both complement and conflict with wider social, economic and environmental priorities with the extent of those complements and conflicts found to vary between places.

The GHG savings from electrifying the bus network ranges from as little as 4 kt CO_2e in Swansea, to more than 500 kt CO_2e in Liverpool. Electrification of the freight network generates financial benefits of £10/tonne GHG mitigated in Manchester, but costs £79/tonne in Cambridgeshire and Peterborough. The social benefits of insulation vary from £223/tonne GHG saved in Cambridgeshire and Peterborough to £285/tonne GHG saved in Belfast.

The differences in the costs and benefits of action between regions are driven in part by the technical and built environment context. The scope for increasing non-motorised and public transport is relatively higher in Glasgow than Cambridgeshire and Peterborough due to Glasgow's relatively higher level of density, which allows more trips to be possible by foot, bicycle or bus.

The social benefits of climate actions, but not the carbon benefits or financial benefits, are also affected by the socio-economic context. An increase in walking and cycling that reduces private car travel reduces the same amount of GHG emissions and energy expenditure in Glasgow as in Cambridgeshire and Peterborough. The benefits to public health from this shift, however, will be larger in Glasgow due to the population being relatively older and facing higher rates of a range of public health ailments.

More research is urgently needed to further explore how aspects of local context affect the benefits and costs of climate actions and the distribution of those benefits and costs. Even as the overall benefits of action far out-weigh the costs, the scale of benefits from non-motorised transport options, for example, may accrue disproportionately to those members of the population who can more easily increase walking and cycling—a younger and more urban population (Davis 2014). Similarly, the costs of retrofitting older buildings may fall disproportionally on an older and more rural population (Kerr et al. 2018).

Common findings are also found across urban regions in this analysis. Measures that shift travel from private cars to non-motorised and public transport options generate substantial social and financial benefits in all city regions. The case for heating and energy efficiency measures is driven by carbon savings rather than social or financial benefits. The dimension of cost/benefit (social, carbon and financial) largest for an intervention in one urban region is almost always the largest dimension of cost/benefit for that intervention in all regions. Across all types of measures in this analysis at most two of the three dimensions of costs and benefits (financial, social and carbon) is found to underpin the case for action.

Common aspects of the socio-economic and technical context underlie these findings. Differences between the results in this study and literature assessing similar measures in the same or similar contexts, however, highlight the importance of methodological choices for shaping our understanding of the co-benefits of climate action. Per capita differences in the health benefits of climate action, for example, are found to be 4–13 × larger in this analysis than in existing literature applying UK CCC climate action pathways (Forster et al. 2013; Milner et al. 2023), due to larger increases in active travel in this analysis.

Making the methodological decisions that lead to different conclusions about the scale of some co-benefits more visible may be increasingly important for advancing understanding of the social case for climate action. While climate action to date in the UK, US, EU, and China has been led by action in the electricity sector (Boehm et al. 2023), climate action in the future in these and other nations will need to shift to emissions from buildings, transport. Action will therefore necessarily shift from urban hinterlands to urban centres, from a relatively small number of actors to every household and business, and from a set of interventions that are often highly technical to interventions such as bicycle riding and thermal insulation that are prosaic but politically and socially complex. Climate action will also need to take place orders of magnitude more quickly.

Approaches for making complex methodologies more transparent and nuanced analyses more accessible include documenting research decisions, making datasets, code, and methodologies more easily accessible, and greater emphasis on comparing results with existing literature (Gelman 2018; Yarkoni 2022; Sudmant et al. 2024). Researchers can also differentiate between the concepts of generalisability and replicability to support the development of more integrated and interdisciplinary research (Sudmant et al. 2024).

Generalisability refers to the extent research findings in one context may apply in another context. The scale of social benefits from shifting to non-motorised transport, for example, are likely to generalise across the urban UK and to other wealthy urban contexts where levels of physical activity are significantly below recommended levels, where air quality and risks of traffic accidents are comparable, and where the demographic profile is similar. In developing contexts, however, where there are frequently many more young people than old, and where health risks from traffic accidents and air quality faced by those using non-motorised transport are much higher in some cases (Borck & Schrauth 2021; Damani & Vedagiri 2021), further research is needed.

Replication refers to the challenges associated with confirming the results of studies and comparing them with other similar studies. At the core of the challenge of replication is the need to compare the construct validity of the frameworks and operationalisations researchers use. Health co-benefits from physical activity in this analysis, for example, are operationalised with relationships between levels of cycling/walking, age-specific mortality, and the value of a life year from the UK Greenbook. This approach is different from an approach that applies a quality-adjusted life year, or a disability adjusted life year. The different ways co-benefits are operationalised and the different choices of co-benefits studies consider are both challenges that affect the replicability of research.

Conclusion

Including the social impacts of climate actions in economic assessment of climate action enhances the case for action. Arguably of greater importance, integrating social and climate challenges in economic analysis is a first step towards integrating policy approaches and action.

Employing replication and generalisability (Sudmant et al. 2024) as boundary objects, concepts that are commonly understood across disciplines (Akkerman & Bakker 2011; Star & Griesemer 1989), offers a means to develop more integrated and interdisciplinary approaches of climate assessment. The concept of replication serves as a meeting point for research that considers the different kinds of impacts that can be considered co-benefits and the different ways those co-benefits can be operationalised through methodologies. The concept of generalisability serves as a meeting point for research considering when co-benefits research in one context can provide insight into the wider impacts of climate action in other contexts.

The development of more integrated approaches to the economic assessment of climate actions can also benefit from more deliberate and transparent approaches to the normative aspects of co-benefits analysis. Leadership in making normative assumptions more visible could come from climate institutions in the UK, including the UK Climate Change Committee, The Yorkshire and Humber Climate Commission and The Scottish Climate Intelligence Service.

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Author contribution Andrew Sudmant, Dom Boyle and Andy Gouldson led the study design and conceptualisation. The first draft of this paper was written by Andrew Sudmant and Ruaidhri Higgin-Lavery. Analytical modelling was led by Dom Boyle. Figures were designed and developed by Ruaidhri Higgin-Lavery. All authors provided feedback on the draft and approved the final version.

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Declarations

Conflict of interest The authors declare no competing interests.

References

Akkerman SF, Bakker A (2011) Boundary crossing and boundary objects. Rev Educ Res 81(2):132–169. https://doi.org/10.3102/0034654311404435

Bain PG, Milfont TL, Kashima Y, Bilewicz M, Doron G, Garðarsdóttir RB, Gouveia VV, Guan Y, Johansson L-O, Pasquali C, Corral-Verdugo V, Aragones JI, Utsugi A, Demarque C, Otto S, Park J, Soland M, Steg L, González R, Saviolidis NM (2016) Co-benefits of addressing climate change can motivate action around the world. Nat Clim Chang 6(2):154–157. https://doi.org/10.1038/nclimate2814

Beatty C, Fothergill S (1996) Labour market adjustment in areas of chronic industrial decline: the case of the UK Coalfields. Reg Stud 30(7):627–640. https://doi.org/10.1080/00343409612331349928

Bergquist P, Mildenberger M, Stokes LC (2020) Combining climate, economic, and social policy builds public support for climate action in the US. Environ Res Lett 15(5):054019. https://doi.org/10.1088/1748-9326/ab81c1

Boehm S, L Jeffery, J Hecke, C Schumer, J Jaeger, C Fyson, K Levin, A Nilsson, S Naimoli, E Daly, J Thwaites, K Lebling, R Waite, J Collis, M Sims, N Singh, E Grier, W Lamb, S Castellanos, A Lee, M Geffray, R Santo, M. Balehegn, M Petroni, M. Masterson (2023) State of Climate Action 2023. Berlin and Cologne, Germany, San Francisco, CA, and Washington, DC: Bezos Earth Fund, Climate Action Tracker, Climate Analytics, ClimateWorks Foundation, NewClimate Institute, the United Nations Climate Change High-Level Champions, and World Resources Institute. https://doi.org/10.46830/wrirpt.23.00010.

Borck R, Schrauth P (2021) Population density and urban air quality. Reg Sci Urban Econ 86:103596. https://doi.org/10.1016/j.regsciurbeco.2020.103596

Bowen A, Kuralbayeva K (2015) Looking for green jobs: The impact of green growth on employment, p 32. Available from https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2015/03/Looking-for-green-jobs_theimpact-of-green-growth-on-employment.pdf

Brand C, Dons E, Anaya-Boig E, Avila-Palencia I, Clark A, de Nazelle A, Gascon M, Gaupp-Berghausen M, Gerike R, Götschi T, Iacorossi F, Kahlmeier S, Laeremans M, Nieuwenhuijsen MJ, Pablo Orjuela J, Racioppi F, Raser E, Rojas-Rueda D, Standaert A, IntPanis L (2021) The climate change mitigation effects of daily active travel in cities. Transp Res Part D: Transp Environ 93:102764. https://doi.org/10.1016/j.trd.2021.102764

CCC (2019) Reducing UK emissions – 2019 Progress Report to Parliament. Climate Change Committee. Available from https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/

CCC (2022) 2022 Progress Report to Parliament. Climate Change Committee. Available from https://www.theccc.org.uk/publication/2022-progress-report-to-parliament/

Colenbrander S, Gouldson A, Sudmant AH, Papargyropoulou E, Chau LW, Ho CS (2016) Exploring the economic case for early investment in climate change mitigation in middle-income countries: A case study of Johor Bahru Malaysia. Clim Dev 8(4):351–364

Colenbrander S, Gouldson A, Roy J, Kerr N, Sarkar S, Hall S, Sudmant A, Ghatak A, Chakravarty D, Ganguly D (2017) Can low-carbon urban development be pro-poor? The case of Kolkata India. Environ Urban 29(1):139–158

Creutzig F (2022) Fuel crisis: Slash demand in three sectors to protect economies and climate. Nature 606(7914):460–462. https://doi.org/10.1038/d41586-022-01616-z

Damani J, Vedagiri P (2021) Safety of motorised two wheelers in mixed traffic conditions: Literature review of risk factors. J Traffic Transportation Eng (english Edition) 8(1):35–56. https://doi.org/10.1016/j.jtte.2020.12.003

Davis A (2014) Claiming the Health Dividend: A summary and discussion of value for money estimates from studies of investment in walking and cycling. Department for Transport. Available from

Emden J, Sudmant A, Farinha T (2024) Skills matter: shaping a just transition for workers in the energy sector. Institute for Public Policy Research. Available from https://www.ippr.org/articles/skills-matter#:~:text=The%20transition%20to%20a%20net,workers%20in%20the%20gas%20sector

Forster D, Korkeala O, Warmington J, Holland M, Smith A (2013) Review of the impacts of carbon budget measures on human health and the environment. Climate Change Committee. Available from https://theccc.org.uk/publication/review-of-the-impacts-of-carbon-budget-measures-on-human-health-and-the-environment-by-ricardo-aea/

Gelman A (2018) How to think scientifically about scientists' proposals for fixing science. Socius 4:2378023118785743

Giglio S, Kelly B, Stroebel J (2021) Climate Finance. Annu Rev Financ Econ 13(1):15–36. https://doi.org/10.1146/annurev-financial-102620-103311

Gouldson A, Colenbrander S, Sudmant A, McAnulla F, Kerr N, Sakai P, Hall S, Papargyropoulou E, Kuylenstierna J (2015) Exploring the economic case for climate action in cities. Glob Environ Chang 35:93–105. https://doi.org/10.1016/j.gloenvcha.2015.07.009

Gouldson A, Sudmant A, Khreis H, Papargyropoulou E (2018) The Economic and Social Benefits of Low-Carbon Cities: A Systematic Review of the Evidence. 92

Gouldson A, Sudmant A, Duncan A, Williamson RF (2020) A net-zero carbon roadmap for leeds, p 27

Green F, Gambhir A (2019) Transitional assistance policies for just, equitable and smooth low-carbon transitions: Who, what and how? Clim Policy 1–20. https://doi.org/10.1080/14693062.2019.1

Grubb M, Lange R-J, Cerkez N, Salas P, Sognnaes I (2022) Dynamic determinants of optimal global climate policy. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3752788

HM Treasury (2020) The Green Book 2020. Department of the Treasury

Huang J, Zhang G, Zhang Y, Guan X, Wei Y, Guo R (2020) Global desertification vulnerability to climate change and human activities. Land Degrad Dev 31(11):1380–1391. https://doi.org/10.1002/ldr.3556

Ibrahim N, Kennedy C (2016) A Methodology for Constructing Marginal Abatement Cost Curves for Climate Action in Cities. Energies 9(4):227. https://doi.org/10.3390/en9040227

Ivanova D, Vita G, Wood R, Lausselet C, Dumitru A, Krause K, Macsinga I, Hertwich EG (2018) Carbon mitigation in domains of high consumer lock-in. Global Environ Change 52:117–130. https://doi.org/10.1016/j.gloenvcha.2018.06.006

Jarrett J, Woodcock J, Griffiths UK, Chalabi Z, Edwards P, Roberts I, Haines A (2012) Effect of increasing active travel in urban England and Wales on costs to the National Health Service. The Lancet 379(9832):2198–2205. https://doi.org/10.1016/S0140-6736(12)60766-1

Jaxa-Rozen M, Trutnevyte E (2021) Sources of uncertainty in long-term global scenarios of solar photovoltaic technology. Nat Clim Change 11(3). https://doi.org/10.1038/s41558-021-00998-8

Kerr N, Gouldson A, Barrett J (2018) Holistic narratives of the renovation experience: Using Q-methodology to improve understanding of domestic energy retrofits in the United Kingdom. Energy Res Soc Sci 42:90–99. https://doi.org/10.1016/j.erss.2018.02.018

Köberle AC, Vandyck T, Guivarch C, Macaluso N, Bosetti V, Gambhir A, Tavoni M, Rogelj J (2021) The cost of mitigation revisited. Nat Clim Chang 11(12):1035–1045. https://doi.org/10.1038/s41558-021-01203-6

Lawrence M, Homer-Dixon T, Janzwood S, Rockstöm J, Renn O, Donges JF (2024) Global polycrisis: The causal mechanisms of crisis entanglement. Global Sustainability 7:e6. https://doi.org/10.1017/sus.2024.1

Meeks L (2023) Promising a Greener Paris: Anne Hidalgo's Framing of Environmental Issues in Her Mayoral Campaigns. Environ Commun 17(6):550–565. https://doi.org/10.1080/17524032.2023.2226356

Mercure JF, Pollitt H, Viñuales JE, Edwards NR, Holden PB, Chewpreecha U, Salas P, Sognnaes I, Lam A, Knobloch F (2018) Macroeconomic impact of stranded fossil fuel assets. Nat Clim Change 8(7):588–593. https://doi.org/10.1038/s41558-018-0182-1

Milner J, Turner G, Ibbetson A, Colombo PE, Green R, Dangour AD, Haines A, Wilkinson P (2023) Impact on mortality of pathways to net zero greenhouse gas emissions in England and Wales: A multisectoral modelling study. Lancet Planetary Health 7(2):e128–e136. https://doi.org/10.1016/S2542-5196(22)00310-2

Monasterolo I, Raberto M (2019) The impact of phasing out fossil fuel subsidies on the low-carbon transition. Energy Policy 124:355–370. https://doi.org/10.1016/j.enpol.2018.08.051

Mueller N, Rojas-Rueda D, Salmon M, Martinez D, Ambros A, Brand C, de Nazelle A, Dons E, Gaupp-Berghausen M, Gerike R, Götschi T, Iacorossi F, Int Panis L, Kahlmeier S, Raser E, Nieuwenhuijsen M (2018) Health impact assessment of cycling network expansions in European cities. Prev Med 109:62–70. https://doi.org/10.1016/j.ypmed.2017.12.011

OBR (2021) Climate-related measures in the Budget and Spending Review. Office for Budget Responsibility. Available from https://obr.uk/box/climate-related-measures-in-the-budget-and-spending-review/

Ortiz-Bobea A, Ault TR, Carrillo CM, Chambers RG, Lobell DB (2021) The historical impact of anthropogenic climate change on global agricultural productivity. Nat Clim Change 11(4):306–312. https://doi.org/10.1038/s41558-021-01000-1

Papargyropoulou E, Colenbrander S, Sudmant AH, Gouldson A, Tin LC (2015) The economic case for low carbon waste management in rapidly growing cities in the developing world: The case of Palembang, Indonesia. J Environ Manage 163:11–19. https://doi.org/10.1016/j.jenvman.2015.08.001

Parry NA, Ian WH (n.d.) Reconsidering Climate Mitigation Policy in the UK. IMF. Retrieved June 21, 2024, from https://www.imf.org/en/Publications/WP/Issues/2020/12/04/Reconsidering-Climate-Mitigation-Policy-in-the-UK-49891

Piontek F, Drouet L, Emmerling J, Kompas T, Méjean A, Otto C, Rising J, Soergel B, Taconet N, Tavoni M (2021) Integrated perspective on translating biophysical to economic impacts of climate change. Nat Clim Chang 11(7):563–572. https://doi.org/10.1038/s41558-021-01065-y

Pires APF, Srivastava DS, Marino NAC, MacDonald AAM, Figueiredo-Barros MP, Farjalla VF (2018) Interactive effects of climate change and biodiversity loss on ecosystem functioning. Ecol 99(5):1203–1213. https://doi.org/10.1002/ecy.2202

Rauner S, Hilaire J, Klein D, Strefler J, Luderer G (2020) Air quality co-benefits of ratcheting up the NDCs. Clim Change 163(3):1481–1500. https://doi.org/10.1007/s10584-020-02699-1

Romanello M, Di Napoli C, Green C, Kennard H, Lampard P, Scamman D, Walawender M, Ali Z, Ameli N, Ayeb-Karlsson S (2023) The 2023 report of the Lancet Countdown on health and climate change: The imperative for a health-centred response in a world facing irreversible harms. Lancet 402(10419):2346–2394

Romanello, M., Napoli, C. D., Drummond, P., Green, C., Kennard, H., Lampard, P., Scamman, D., Arnell, N., Ayeb-Karlsson, S., Ford, L. B., Belesova K, Bowen K, Cai W, Callaghan, M, Campbell-Lendrum D, Chambers J, Daalen K. R van, Dalin C, Dasandi N, … Costello A (2022) The 2022 report of the Lancet Countdown on health and climate change: Health at the mercy of fossil fuels. The Lancet, 0(0). https://doi.org/10.1016/S0140-6736(22)01540-9

Santamouris M (2020) Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact. Synergies with the global climate change. Energy Build 207:109482. https://doi.org/10.1016/j.enbuild.2019.109482

Shiraki H, Sugiyama M (2020) Back to the basic: Toward improvement of technoeconomic representation in integrated assessment models. Clim Change 162(1):13–24. https://doi.org/10.1007/s10584-020-02731-4

Star SL, Griesemer JR (1989) Institutional Ecology, "Translations" and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907–39. Soc Stud Sci 19(3):387–420

Stern N (2022) Towards a Carbon Neutral Economy: How Government Should Respond to Market Failures and Market Absence. J Gov Econ 6:100036. https://doi.org/10.1016/j.jge.2022.100036

Stern, N. (2007). The Economics of Climate Change: The Stern Review. Cambridge University Presshttps://doi.org/10.1017/CBO9780511817434

Sudmant A, Millward-Hopkins J, Colenbrander S, Gouldson A (2016) Low carbon cities: Is ambitious action affordable? Clim Change 138(3–4):681–688

Sudmant AH, Gouldson A, Colenbrander S, Sullivan R, McAnulla F, Kerr N (2017) Understanding the case for low-carbon investment through bottom-up assessments of city-scale opportunities. Climate Policy 17(3):299–313

Sudmant, Creutzig, He (2024) Replicate and generalize to make urban research coherent. Int J Urban Sci. Under review

Svenningsen LS (2019) Social preferences for distributive outcomes of climate policy. Clim Change 157(2):319–336. https://doi.org/10.1007/s10584-019-02546-y

TAG (2021) Transport Analysis Guidance. Department for Transport. Available from https://www.gov.uk/guidance/transport-analysis-guidance-tag

Ürge-Vorsatz D, Herrero ST, Dubash NK, Lecocq F (2014) Measuring the Co-Benefits of Climate Change Mitigation. Annu Rev Environ Resour 39(1):549–582. https://doi.org/10.1146/annurev-environ-031312-125456

Vandyck T, Keramidas K, Tchung-Ming S, Weitzel M, Van Dingenen R (2020) Quantifying air quality co-benefits of climate policy across sectors and regions. Clim Change 163(3):1501–1517. https://doi.org/10.1007/s10584-020-02685-7

Vicedo-Cabrera AM, Scovronick N, Sera F, Royé D, Schneider R, Tobias A, Astrom C, Guo Y, Honda Y, Hondula DM, Abrutzky R, Tong S, de Coelho MSZS, Saldiva PHN, Lavigne E, Correa PM, Ortega NV, Kan H, Osorio S, … Gasparrini A (2021) The burden of heat-related mortality attributable to recent human-induced climate change. Nat Clim Change 11(6):492–500. https://doi.org/10.1038/s41558-021-01058-x

Victoria M, Haegel N, Peters IM, Sinton R, Jäger-Waldau A, del Cañizo C, Breyer C, Stocks M, Blakers A, Kaizuka I, Komoto K, Smets A (2021) Solar photovoltaics is ready to power a sustainable future. Joule 5(5):1041–1056. https://doi.org/10.1016/j.joule.2021.03.005

Vogt-Schilb A, Hallegatte S (2014) Marginal abatement cost curves and the optimal timing of mitigation measures. Energy Policy 66:645–653. https://doi.org/10.1016/j.enpol.2013.11.045

Way R, Ives MC, Mealy P, Farmer JD (2022) Empirically grounded technology forecasts and the energy transition. Joule 6(9):2057–2082. https://doi.org/10.1016/j.joule.2022.08.009

Weitzman M (2009) On Modeling and Interpreting the Economics of Catastrophic Climate Change. Rev Econ Stat 91(1):1–19

Williamson RF, Sudmant A, Gouldson A, Brogan J (2020) A Net-Zero Carbon Roadmap for Edinburgh. 27

Willis DP, Manaugh K, El-Geneidy A (2015) Cycling under influence: summarizing the influence of perceptions, attitudes, habits, and social environments on cycling for transportation. Int J Sustain Transp 9(8):565–579. https://doi.org/10.1080/15568318.2013.827285

Winkler L, Pearce D, Nelson J, Babacan O (2023) The effect of sustainable mobility transition policies on cumulative urban transport emissions and energy demand. Nature Communications, 14(1), Article 1. https://doi.org/10.1038/s41467-023-37728-x

Yarkoni T (2022) The generalizability crisis. Behavioral and Brain Sciences, 45. https://doi.org/10.1017/S0140525X20001685