BUILDINGS & CITIES

A residential emissions-based carbon levy: city and neighbourhood consequences

RESEARCH

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ABSTRACT

What are the consequences of a local carbon levy applied to (1) all estimated residential consumption emissions and (2) all residential gas and grid electricity-related emissions? Housing stock simulations in the City of Southampton, UK, are used to explore whether a local carbon levy could pay for retrofits at a local level. The value of the levy is estimated for the whole city and for neighbourhoods at the census lower layer super output area (LSOA) level (about 1500 households) using recently published 'official' carbon values under two scenarios. The levy is then set against an estimate of the cost of retrofitting energy-efficient dwellings in each LSOA. The models show that highly emitting LSOAs (generally those with least deprivation) would raise sufficient levy to retrofit their dwellings within three to five years if an 'all emissions' levy were applied. This is not the case in low-emissions LSOAs which tend to be those with the highest deprivation. Here it could take up to 60 years to meet the retrofit costs if the levy were only applied to energy emissions. Redistribution of the levy from the least deprived but highly emitting neighbourhoods to the more deprived but least emitting would therefore be needed.

PRACTICE RELEVANCE

This paper shows that a local area carbon levy on residential emissions would not self-fund energy efficiency upgrades in the City of Southampton's dwelling stock 'to a reasonable standard' within an acceptable time frame. It would only be effective in high-emissions areas, and the levy would need to be redistributed to lower emissions (and thus lower levy-generating) areas, which also tend to be those with the highest energy poverty and worst housing. The paper is therefore evidence of the need for public investment to ensure energy efficiency upgrades occur within a reasonable time frame for those in greatest need. It also shows that innovation in financial models is required to ensure that the rate of upgrade, and thus decrease in energy use, emissions and energy insecurity is accelerated across middle to high emitters who are unlikely to receive direct government support, where their own capital is insufficient and their incentives to invest are relatively low.

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1. INTRODUCTION

There is increasing agreement that reducing energy demand by increasing the energy efficiency of buildings, and especially dwellings, is a crucial part of a transition to net zero emissions by 2050. This is reflected in national and international schemes such as the European Union's (EU) Energy Performance of Buildings Directive (Economidou *et al.* 2020) and the related 'renovation wave' announced as part of the 2020 European Green Deal which are intended to contribute significantly to national energy and climate plans. Despite this recent UK Climate Change Committee communications note that reducing energy demand in UK buildings is now the biggest gap in current energy policy (Lord Deben 2022; Climate Change Committee 2023), while the European Commission's own research reports low (< 2%/year) rates of 'medium' or 'deep' renovations with limited variation across nations (Zangheri *et al.* 2021). This lack of progress is particularly troubling for countries such as the UK where the focus on least-cost measures such as cavity wall (68% insulated in England) and loft insulation compared with more costly measures such as solid-wall insulation (10% insulated) means that the overall housing stock continues to suffer from poor energy efficiency (Friedler & Kumar 2019; Piddington *et al.* 2020).

Given that the cheapest form of energy is that which is not used, reducing household fossil fuel use is also a major plank of a nation's energy security policy and a key response to recent fossil fuel price shocks (BEIS 2022). This has been reflected in recent policy responses to the interdependent 'gas dependency' and 'cost of living' crises in countries such as Germany, Ireland and the Netherlands which plan to bring forward phase-out dates for fossil fuel heating (Braungardt *et al.* 2023). Denmark's use obligation for renewable heating goes a step further, effectively banning fossil fuel use for heating in certain areas. However, these kinds of infrastructural transition measures cannot address short-term inflationary shocks leading to the implementation of emergency fiscal responses such as the UK's Energy Price Guarantee which effectively subsidise the cost of energy at the household level, potentially reducing the financial incentive to implement energy efficiency retrofit. Further, recent research has suggested that current inflationary pressures and uncertainty are likely to disrupt 'market-based' approaches to retrofitting programmes such as those currently in place in the UK (Morgan *et al.* 2023).

The significant capital investment required for large-scale energy efficiency retrofit is recognised as a major barrier to progress (Mohareb *et al.* 2022), with estimates in the order of £250–300 billion for the UK alone (Climate Change Committee 2020). At the individual dwelling level, anticipated costs of retrofitting 'to an appropriate standard' in the UK have been suggested to range from £13,300 for about a £460 annual energy cost saving on a relatively efficient property to £26,800 (about £1690 savings) for the least efficient (MHCLG 2018), although these values hide substantial and significant heterogeneity due to the variations in existing built form. More recent analysis suggests that:

> over 60% of households can achieve levels of energy efficiency that are compatible with Net Zero for less than £1,100. The average costs for all households are higher, at over £10,900 […].
>
> (Lord Deben 2022: 13;
> see also Climate Change Committee 2020; Raslan *et al.* 2020)

These costs are argued to makes the case for switching public funding from operating cost subsidy schemes such as the Energy Price Guarantee to direct energy efficiency investment as well as enabling access to market-based private finance approaches in the context of increasing interest rates and inflationary pressures (Lord Deben 2022).

The case for a market-based approach in the UK follows from estimated annual rates of return of between 4% and 6% (MHCLG 2018) even under 2018 energy prices. However, consumers are known not to make 'rational economic' retrofit decisions, even where they have access to the required capital and may prefer not to make such disruptive investments, especially when there may be a risk that they will not recoup the investment before a dwelling sale (Friedler & Kumar 2019; Chisholm *et al.* 2019). Historically there have been even fewer incentives for landlords who would benefit little from retrofit where tenants pay the dwelling's energy costs (Ambrose 2015; März 2018; Cremer & Weber 2022), although this is, to some extent, now being mediated by minimum energy efficiency standards for rented properties in many jurisdictions (Zangheri *et al.* 2021). The lack of economic incentive to invest is especially the case for wealthier households whose energy expenditures form a much smaller proportion of their overall outgoings (Ofgem 2015; Faiella & Lavecchia 2021). As a result, the opportunity and disruptive cost of investing for wealthier homeowners is substantial compared with the proportionate savings they would attain with respect to both income and overall household expenditure. It is only recently that research has shown there may be future economic pay-offs through increased dwelling price premiums at time of sale, although it remains unclear whether these will overcome perceived 'payback period' barriers (Aydin *et al.* 2020).

Research has shown that wealthier households tend to be the highest emitters of greenhouse gases whether measured by direct energy use or by wider consumption-based carbon accounting (Büchs & Schnepf 2013). However, the environmental cost of these emissions is currently largely externalised so there are few incentives for high emitters to change (Fleurbaey *et al.* 2019). Considerable recent research has shown that applying a 'polluter pays' carbon tax to measured energy-use driven or estimated consumption emissions could act as a significant lever to enact change, but would also cost poorer households proportionately more due to the carbon footprint of unavoidable consumption such as energy use and food (Büchs *et al.* 2011; Druckman *et al.* 2012; Wang *et al.* 2016; Berry 2019). In the context of retrofit in particular, carbon taxes are seen as both increasing the cost of energy, thus increasing financial incentives to reduce energy use, and at the same acting as a source of funds for incentive programmes (Freyre *et al.* 2020).

This paper explicitly links these two strands by asking whether a locally raised carbon levy could realistically pay for the housing stock retrofit required in that local area. This 'hypothecated' approach, where revenue raised by tax is allocated for a specific purpose, responds to a recent UK Carbon Tax consultation which noted that 'revenues from a Carbon Emissions Tax should be redistributed as dividends across the economy' (HM Revenue & Customs and HM Treasury 2021: 10). In the case of this paper, the redistribution is specifically for energy efficiency upgrades of the existing dwelling stock and could be considered alongside other tax interventions such as adjustments to property purchase taxes (Lord Deben 2022). In this instance the levy would act *both* as an incentive to reduce household level emissions *and* as a source of energy efficiency investment capital. Clearly over time success in the former would reduce the emissions levy revenue and thus capital available for the latter. Ideally this would occur at a rate that enabled the declining levy revenue to pay for the remaining retrofit investments.

Although there have been several studies of the national- and state-level effects of carbon taxes, especially when applied to transport fuels (Murray & Rivers 2015; Andersson 2019), a recent wide-ranging review of the potential for carbon taxes to fund energy programmes for buildings suggests that there have been no published attempts to model the level of revenues that could flow from a more general emissions levy at the local level (Freyre *et al.* 2020). This is most likely because robust data on, or even reasonable estimates of, small area household emissions have historically been lacking since they depend on the kind of spatially disaggregated energy-use data that have only recently become available via smart metering programmes and open-energy data initiatives. Further, although there have been studies of the use of carbon tax revenues to fund national programmes (Ghaith & Epplin 2017; Zhang *et al.* 2017; Freyre *et al.* 2020) and specific building interventions (Royapoor *et al.* 2019), there appear to have been no attempts to model the potential utility of recycling a locally raised emissions levy into local energy efficiency retrofit.

The paper's overall approach is to model the potential revenue that could be generated by a carbon levy on (1) estimated residential consumption-based emissions and (2) measured residential energy emissions at the local area level for the City of Southampton (UK) under two scenarios. The paper then compares these estimated revenue levels with estimates of the cost of retrofitting energy-inefficient properties for local areas in the city. The aim is to understand to what extent local hypothecation within local areas could raise sufficient funds or whether redistribution between areas within the city would be required and the reasons for this. This approach requires data at the

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level of local consumption- and energy-based emissions, the carbon 'cost' of these emissions (as an indicator of levy value), assumptions on retrofit costs for different standards of housing as well as indicators of local housing stock energy efficiency. While the results are necessarily location specific, they are illustrative of urban areas in the wider UK and the methodology could be applied to any other area (or nation) with suitable data.

2. DATA

The paper uses a single source of data for both emissions estimates and counts of dwellings at different levels of energy efficiency: the Centre for Research in Energy Demand Solutions' (CREDS) place-based carbon calculator data for lower layer super output areas (LSOAs) in England (Morgan *et al.* 2021).[1] Each LSOA corresponds to around 1500 households, and the paper reports analysis of the 148 LSOAs in the City of Southampton.

This dataset provides a range of estimates of emissions per person in kg CO_2e for each LSOA. Of these, the categories used in this paper were 2018 estimates for:

- total consumption-based emissions: according to the CREDS data documentation these were estimated using the UK consumption-based carbon footprint,[2] scaled to account for England's population and then distributed to the LSOAs based on middle layer super output area (MSOA)-level estimates of household income[3]
- emissions due to gas use: based on measured gas use at the LSOA level for 2018
- emissions due to electricity use: based on measured electricity use at the LSOA level for 2018

It should be noted that the CREDS data use the national UK gas or electricity grid carbon intensity for the year the energy use was observed to calculate the emissions derived from the measured energy use within each LSOA. As a result, the values take no account of 'green' energy tariffs that could be delivering close to zero carbon electricity, and to some extent gas with appropriate offsetting, to a proportion of households in any LSOA. Further, it is known that there may be a misallocation of non-residential to residential energy use (and vice versa) in both the electricity and gas use datasets (DESNZ 2023). Unfortunately there is currently no way to mitigate this potential source of error. The CREDS data only provide estimates up to and including 2018, and these were chosen to temporally align with the estimates of retrofit costs discussed below.

The CREDS data also contain the then most recent counts (2018) of the number of electricity and gas meters in each LSOA. The former can be used as a proxy for the number of dwellings, but the latter cannot due to areas not connected to the gas network or where gas connections have not been made if heating is purely electric. The data also count the number of dwellings in each Energy Performance Certificate (EPC) band derived from a snapshot of the national publicly available EPC database[4] collected in 2020. This is used in this paper as the basis for the estimation of per LSOA retrofit costs.

Second, the paper uses 'cost of carbon' values published by the UK Department for Business, Energy and Industrial Strategy (BEIS) (2021a) to give a levy value to the emissions calculated. These are shown for the period 2020–22 in Table 1.

YEAR	EMISSIONS (£)		
	LOW	CENTRAL	HIGH
2020	£120	£241	£361
2021	£122	**£245**	£367
2022	£124	£248	£373

Table 1: Carbon values in 2020 prices/tCO_2

Note: The value in bold was used in Scenario 1.

Source: BEIS (2021a).

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Third, the paper uses estimates of the cost of retrofitting dwellings in different EPC bands 'to an appropriate standard' published in a recent English Housing Survey technical report (MHCLG 2018) together with the EPC counts described above as the basis for estimating the per LSOA costs of retrofit (Table 2).

Table 2: Estimated costs of retrofitting 'to an acceptable standard'

ENERGY PERFORMANCE CERTIFICATE BAND	COST (£)
A–E	£13,300
F–G	£26,800

Finally the paper uses Census 2011 data for England to estimate the proportion of households in each LSOA that have electric heating in order to understand the distribution of gas- and electricity-use emissions. Data for 2021 were not used as the CREDS emissions estimates and energy meter counts predate the 2021 Census and use 2011 LSOA boundaries. There have been several LSOA boundary changes between the 2011 and 2021 Censuses which prevent complete LSOA-level linkage of the CREDS data to UK Census 2021 data. Future updates of the model would therefore require all component datasets to update to the 2021 UK Census LSOA boundaries.

In addition to these input data, the paper also uses income deprivation estimates at the LSOA level (MHCLG 2019) to understand and model the distribution of the emissions estimates. Southampton contains LSOAs in all income deprivation deciles with 19 (13%) of the 148 amongst the 10% most deprived in the country and 108 (73%) amongst the 50% most deprived. Just one Southampton LSOA (< 1%) is in the least deprived 10% of LSOAs in England (Figure 1).

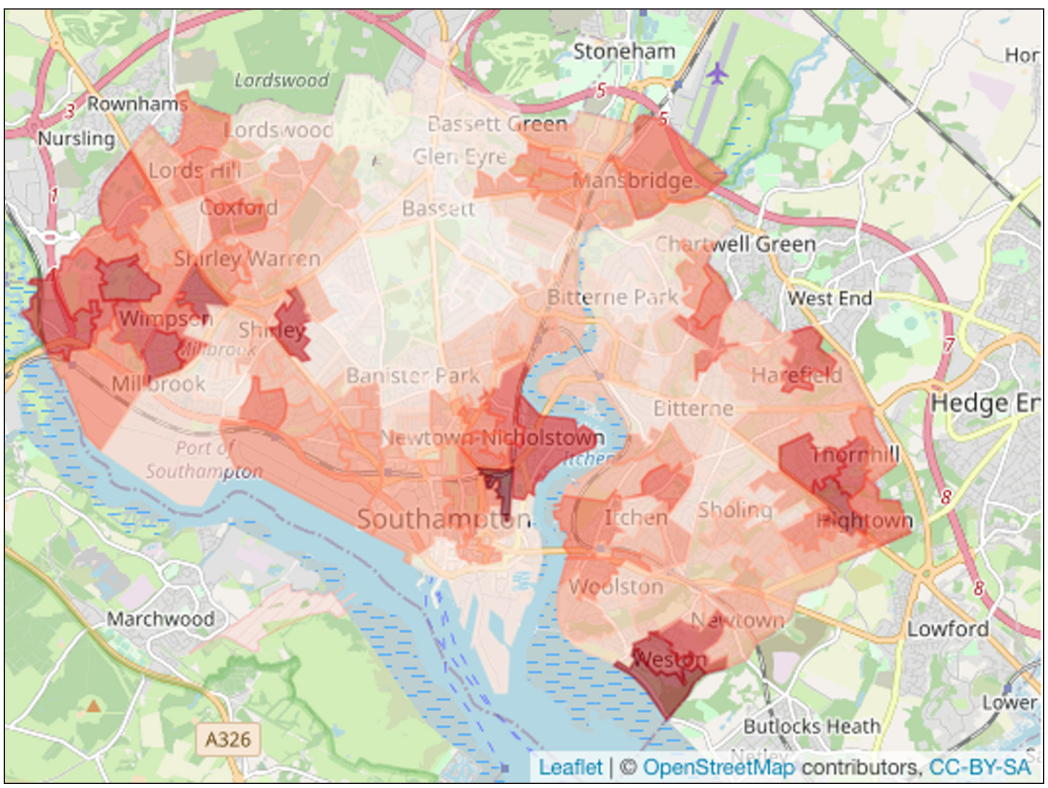

Figure 1: Lower layer super output area (LSOA)-level distribution of multiple deprivation in the City of Southampton.

Note: Areas of higher deprivation are shown in darker shades and are concentrated in Woolston, Bevoir and Redbridge. The more affluent (lighter shaded) area comprises the central Avenue and University Highfield Campus neighbourhoods.

Source: MHCLG (2019).

To give further context, small area-level household income estimates[5] suggest that mean total household income in 2018 was slightly lower (£41,400) in Southampton than in England as a whole (£43,900). In general it would be expected that higher deprivation areas, as measured by the English Index of Multiple Deprivation (IMD) would have higher rates of poor housing as housing quality is one dimension of the indicator. However, the CREDS EPC database snapshot, combined with the IMD decile from the IMD 2019 (MHCLG 2019) shows that the distribution of dwellings by

EPC and index of income deprivation decile in Southampton is notably different from the rest of England (Figure 2). In Southampton, a substantial majority of dwellings are in the more deprived areas (IMD decile < 6) and these also contain a large number of less efficient dwellings (EPC bands D–G), with bands F and G dwellings predominantly found in the most deprived areas.

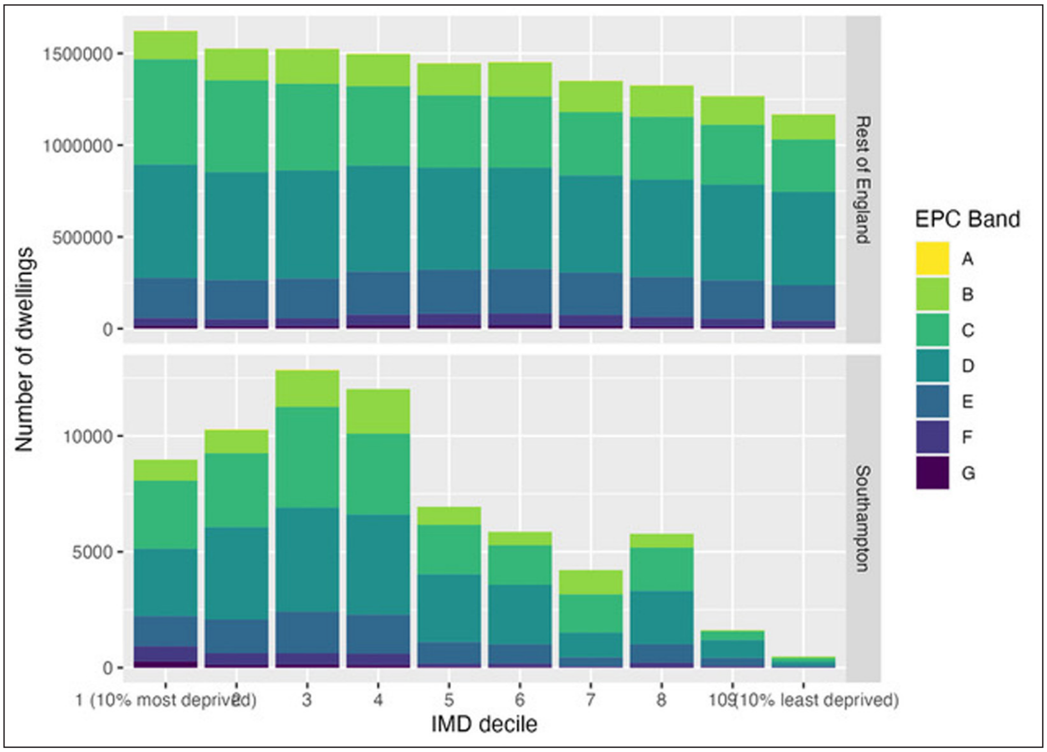

Figure 2: Observed 2020 Energy Performance Certificate (EPC) counts by the 2019 Index of Multiple Deprivation (IMD) decile for Southampton versus the rest of England.

Figure 3 shows the distribution of EPC band dwellings by area-level social rental decile from the UK Census 2011. As would be expected, in England as a whole, areas with higher proportions of social renters tend to have higher levels of bands B and C dwellings, reflecting the effect of social housing new-build and upgrade policies. This is also the case in Southampton, at least in the highest social rental areas, but these areas also contain the highest prevalence of bands E–G dwellings.

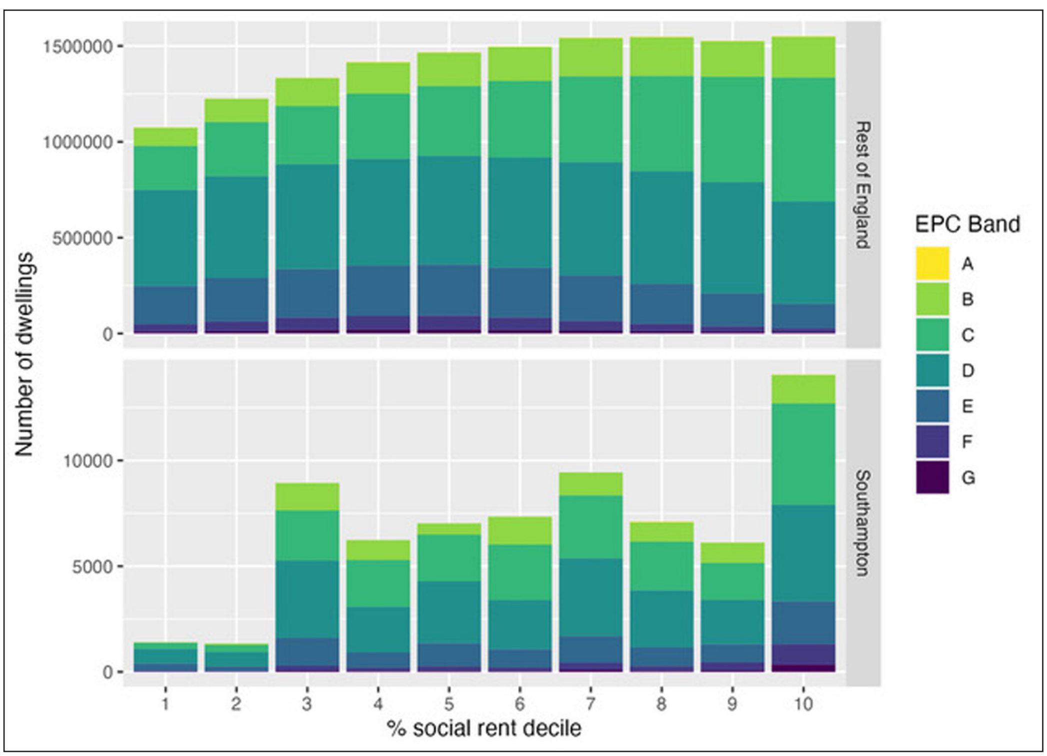

Figure 3: Observed 2020 Energy Performance Certificate (EPC) counts by the percentage of social renters decile for Southampton versus the rest of England.

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In contrast, Figure 4 shows that areas with the highest private rental rates in the UK Census 2011 data also tend to have the highest numbers of poor energy efficiency dwellings (bands E–G) whether in Southampton or England more generally. However, it is also clear that the majority of Southampton dwellings are in areas with high levels of private renting, unsurprising in a city with two universities and where 14% of Census 2021 respondents were students compared with 8% for the whole of England.[6]

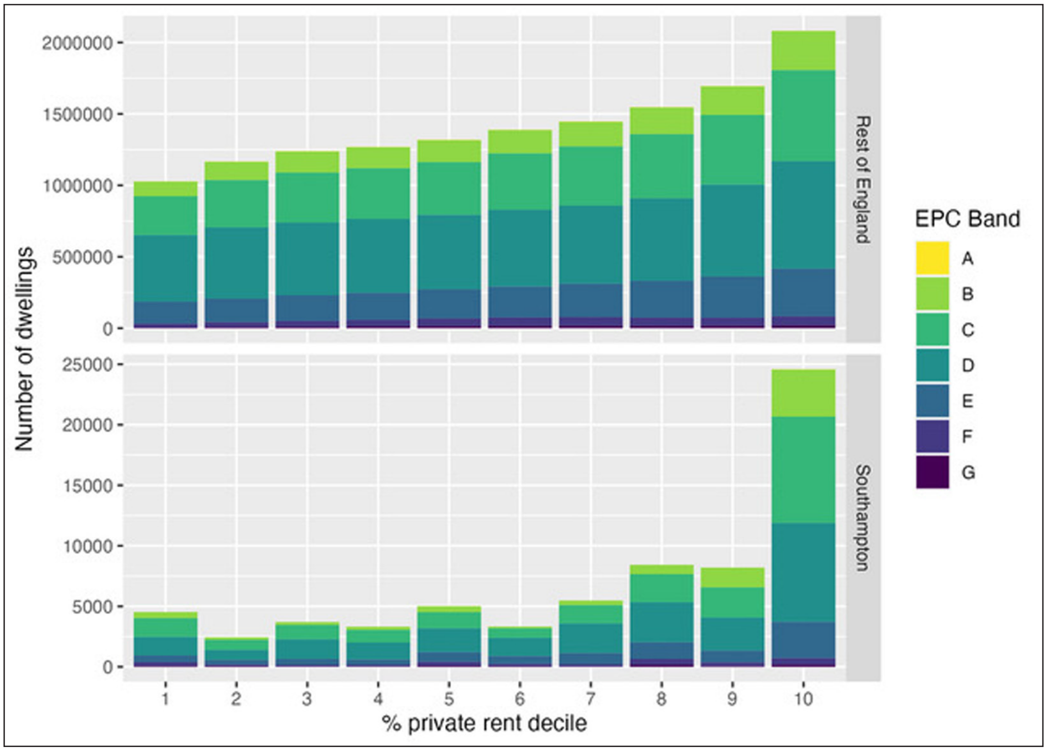

Figure 4: Observed 2020 Energy Performance Certificate (EPC) counts by the percentage of private renters (in 2011, lower layer super output area (LSOA) level) decile for Southampton versus the rest of England.

Finally, compared with the rest of England, UK 2021 Census data show that the City of Southampton has a higher proportion of flats (42% versus 22%) and, as might be expected from the 2011 data reported above, a higher proportion of both social renters (22% versus 17%) and private renters (29% versus 21%). This is also reflected by the number of bedrooms with 21% of households having only one bedroom compared with 11% in England, and only 12% have four or more bedrooms compared with 21% in England as a whole.

3. METHODS

3.1 ESTIMATING PER HOUSEHOLD EMISSIONS

The CREDS estimated per person emissions data were converted to total emissions per LSOA for each of the three emissions categories of interest by multiplying by the LSOA population estimate provided by the CREDS data. These values were then converted to per dwelling values by dividing by the number of electricity meters in each LSOA recorded in the CREDS data as a proxy for the number of dwellings.

Table 3: Mean per dwelling emissions estimates for a range of sources

Source: CREDS: Southampton lower layer super output areas (LSOAs) (tCO_2e).

SOURCE	tCO_2e/YEAR	% OF TOTAL	MINIMUM–MAXIMUM (tCO_2e)
All consumption-based emissions	17.13		5.85–44.96
Gas use	1.76	10.3%	0.01–3.66
Electricity use	1.00	5.8%	0.66–1.46
Other energy use	0.12	0.7%	0.00–1.15
Personal transport use	2.11	12%	0.76–4.22

The resulting per dwelling emissions estimates are shown in Table 3. The mean LSOA level 'All consumption-based emissions' total per dwelling was 17.13 tCO_2e/year with a minimum of 5.85 tCO_2e and a maximum of 44.96 tCO_2e in the highest emitting LSOA. Emissions from gas use, which is predominantly heating, hot water and some cooking in the UK, were approximately 10% of all per dwelling emissions, while those from electricity were lower still. Table 3 also includes 'Other energy use' to illustrate the relative insignificance of this category in an urban area such as Southampton. Transport-related emissions are included for reference, but other consumption and service-usage emissions, which comprise the bulk of the total emissions value of 17 tCO_2e per dwelling, are excluded for clarity.

3.2 ESTIMATING THE VALUE OF A HOUSEHOLD EMISSIONS LEVY

Two levy scenarios were used in this analysis as a basis for estimating the potential value of a household emissions levy:

- the simple application of the central value for 2021 of £245/tonne CO_2e emitted (highlighted in Table 1) and
- a rising block tariff that applied progressively higher rates to blocks of consumption over a given threshold: such tariffs are intended to increasingly penalise those who consume more (Zetland & Gasson 2013)

In the first scenario, the LSOA level per dwelling 'all consumption', 'gas use' and 'electricity use' CO_2e emissions values were multiplied by the 2021 Central carbon value highlighted in Table 1. This gave an LSOA level per dwelling annual carbon emissions levy value. As a simple multiplier this value followed the same distribution as the emissions shown in Table 3. The total levy value under Scenario 1 was then calculated by multiplying the per dwelling total by the number of dwellings in each LSOA.

Table 4: Scenario 2 carbon values' thresholds

CARBON COST (£)	THRESHOLD (%)	THRESHOLDS BY EMISSIONS SOURCE (TCO_2E PER DWELLING PER YEAR)		
		ALL CONSUMPTION	GAS	ELECTRICITY
£122	< 25%	< 11.9	< 1.4	< 0.9
£245	25–50%	11.9–15.5	1.4–1.7	0.9–0.99
£367	> 50%	> 15.5	> 1.7	> 0.99

In the second scenario the three (low, central, high) carbon costs were applied to LSOA level per dwelling emissions values between specific thresholds. In the absence of guidance as to what these thresholds should be for an emissions levy, this paper chose two relatively arbitrary thresholds: 25% and 50% of relevant emissions source distributions (Table 4). As with any rising block tariff, the first 25% of the per dwelling emissions was set to the lower value. Any emissions in the 25–50% thresholds were set to the central value and any emissions over the 50% threshold (median) were set to the high value.

Having estimated the potential value of funds available from a simple emissions levy in each LSOA, the next step was to estimate the cost of retrofitting dwellings in each LSOA 'to an acceptable standard'.

3.3 ESTIMATING DWELLING EPC COUNTS PER LSOA

The CREDS data contain a count of the number of dwellings in each EPC band A–G for each LSOA derived from the national EPC database at the time the data were created. Since EPCs are only required for rental, for new builds and on dwelling sales in England, it is well known that the EPC database does not yet have 100% dwelling coverage. Setting aside additional issues of inaccuracy and error (Jenkins *et al.* 2017; Crawley *et al.* 2019), for the purposes of this paper the 'missing' EPCs were imputed by reweighting the EPC band counts in each LSOA so that they sum to the number of households inferred from the number of electricity meters. While this method assumes that EPCs are essentially missing at random and in proportion, the method is transparent and can easily be amended in future work with more accurate LSOA-level data.

The result of this process is an estimate of the number of dwellings in each EPC band (A–G) for each LSOA. The Southampton results can then be used as the basis for a per LSOA retrofit cost estimate using per dwelling estimated costs of retrofit for each EPC band.

As Table 5 shows, the estimated distribution of EPCs in the City of Southampton is relatively close to the distribution for all English LSOAs provided by the CREDS data. In conjunction with the contextual data discussed above, this suggests that Southampton is a useful representative case study of the approach.

EPC BAND	CITY OF SOUTHAMPTON		ALL ENGLISH LSOAS	
	NUMBER OF DWELLINGS	%	NUMBER OF DWELLINGS	%
A	124	0.12%	39,885	0.17%
B	12,081	11.29%	2,513,218	10.79%
C	33,672	31.47%	6,667,431	28.61%
D	41,797	39.06%	9,628,696	41.32%
E	15,469	14.46%	3,743,328	16.06%
F	2,763	2.58%	502,139	2.15%
G	1,105	1.03%	207,380	0.89%

Table 5: Imputed number of dwellings by Energy Performance Certificate (EPC) band for the City of Southampton versus all English lower layer super output areas (LSOAs)

3.4 ESTIMATING PER DWELLING 'RETROFIT COSTS'

Previous work estimating the potential retrofit costs of the UK building stock has used several methods, including modelling specific interventions (Climate Change Committee 2020; Raslan *et al*. 2020) and whole-house approaches (Friedler & Kumar 2019). In the absence of a disaggregated detailed residential building stock model for Southampton that could be used to model specific per dwelling interventions, this paper used the EPC band upgrade estimates presented in Table 2 and applied them to the imputed counts of dwellings in each EPC band in each LSOA.

It was assumed that dwellings in the least energy-efficient EPC bands (D–G) would be prioritised and that EPC bands A–C would *not* be retrofitted since they would already conform to the current UK policy objective of:

> as many homes as possible to achieve EPC band C by 2035 where cost-effective, practical and affordable, and to ensure as many fuel poor homes as reasonably practicable achieve a band C rating by the end of 2030.
>
> (BEIS 2021b)

The retrofit costs of band A–C dwellings (representing about 43% of dwellings) (Table 5) were therefore set to zero before the total retrofit costs for each EPC band in each LSOA were summed. Future work could examine the effects of including further bands in the calculation and of more nuanced retrofit cost estimates based on a more detailed residential building stock model.

Overall, this method produced an estimated retrofit cost for all EPC bands D and E dwellings in Southampton of about £762 million (57,266 dwellings) and about £146 million for all bands F and G dwellings (n = 3868), giving a total of approximately £908 million.

Figure 5 shows the resulting total estimated dwelling retrofit costs by deprivation decile. As would be expected from the contextual data for Southampton presented above (especially Figure 2), the majority of the costs would be incurred in areas of higher deprivation where the prevalence of poor-quality housing is highest.

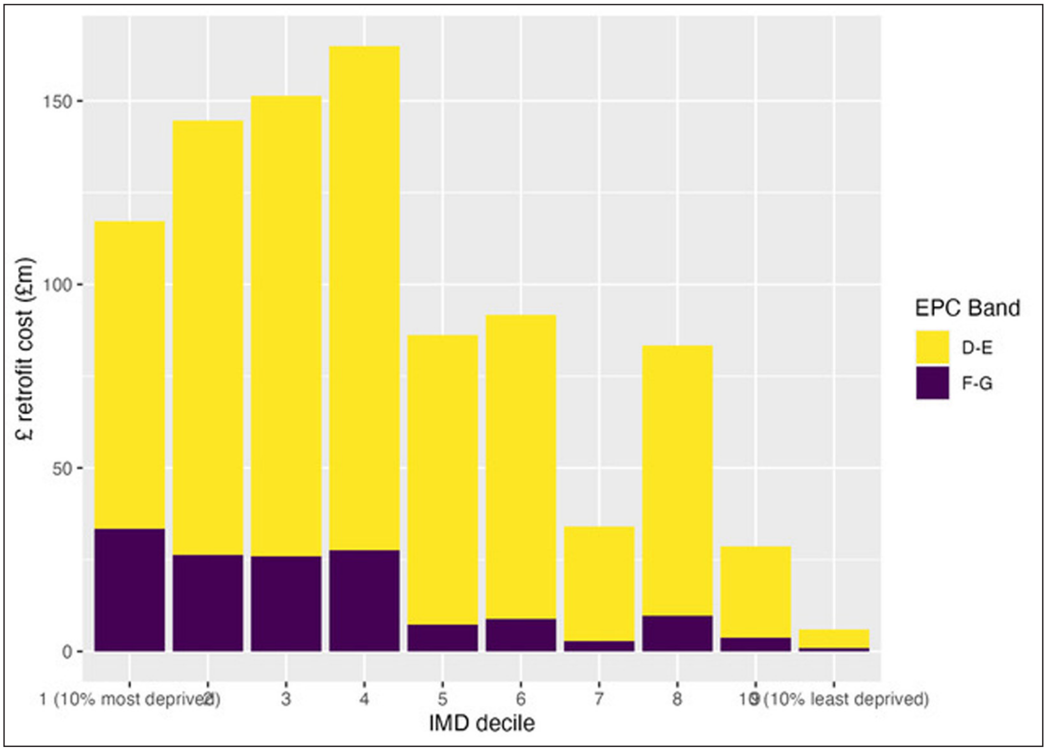

Figure 5: Sum of lower layer super output area (LSOA)-level dwelling bands D–G retrofit costs by LSOA-level 2019 Index of Multiple Deprivation (IMD) score deciles.

4. RESULTS

4.1 SCENARIO 1: CENTRAL CARBON VALUE

This section reports the results of applying the single central carbon value to the emissions.

4.1.1 Per dwelling emissions levy

The total levy value for the 'all consumption' residential emissions for Southampton under Scenario 1 was estimated to be £435 million in year 1. For comparison, this is roughly half the total retrofit costs estimated above. For gas emissions only, the levy total was £45 million, but was £27 million if electricity emissions were used.

The highest and lowest emitting and thus the highest (lowest) emissions levy LSOAs under each of the three emissions sources in this scenario are shown in Table 6. It also shows the annual levy as a percentage of the estimated local small area-level total household income.[7] It is immediately obvious that the lowest gas using LSOA is also the highest electricity using LSOA, reflecting the LSOA-level prevalence of electric heating. It is also clear that dwellings in the most emitting LSOA would face a significant levy charge of nearly 20% of estimated average total income were 100% of the 'All consumption' levy be collected. Nevertheless, this represents the carbon cost of the levels of consumption estimated for this LSOA, which, while in overall deprivation decile 8, was also in the least income deprived decile (10).

Table 6: Highest and lowest layer super output area (LSOA)-level emissions and carbon costs per dwelling by source (based on the £245/tCO_2 scenario)

Note: IMD = Index of Multiple Deprivation.

EMISSIONS SOURCE	LSOA	DEPRIVATION (IMD) DECILE	WARD	tCO_2e PER DWELLING PER YEAR	CARBON COST PER DWELLING PER YEAR (£)	ESTIMATED TOTAL ANNUAL HOUSEHOLD INCOME (£)	% OF ESTIMATED ANNUAL INCOME
All consumption	E01017249	8	Shirley	44.96	£11,015	£58,400	18.9%
	E01017140	3	Bargate	5.80	£1,432	£34,100	4.2%
Gas use	E01017249	8	Shirley	3.66	£897	£58,400	1.5%
	E01032746	7	Bargate	0.01	£3	£40,800	0.0%
Electricity use	E01032746	7	Bargate	1.46	£358	£40,800	0.9%
	E01017278	4	Woolston	0.66	£161	£34,100	0.5%

Figure 6 illustrates the relationship between emissions levy (and hence emissions) and overall deprivation at the LSOA level for all 148 Southampton LSOAs. The relationship between area-level deprivation and consumption emissions is clear with three LSOAs in the ninth (second least deprived) IMD decile being significantly higher emitters with a resulting per dwelling emissions levy of over £10,000 per year.

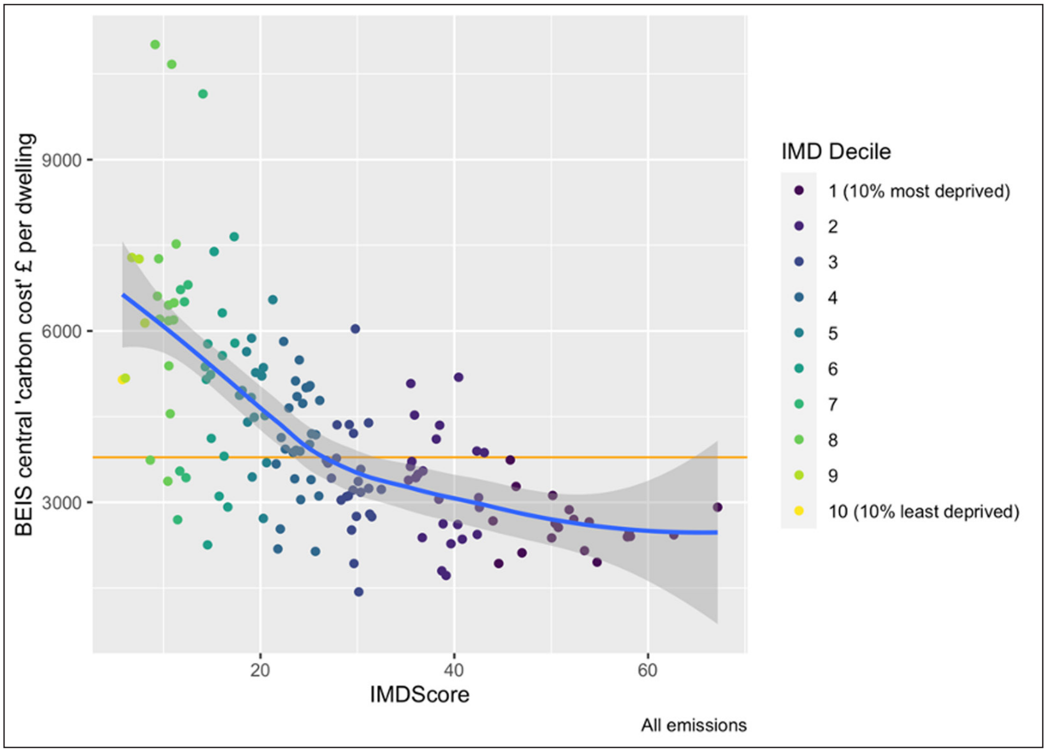

Figure 6: Lower layer super output area (LSOA) level per dwelling carbon 'levy' for 'all consumption emissions' against the 2019 Index of Multiple Deprivation (IMD) score.

Notes: Coloured by the score decile, median £ cost per dwelling is plotted. The smoothed line is fitted using locally estimated scatterplot smoothing (LOESS) (Wickham 2016).

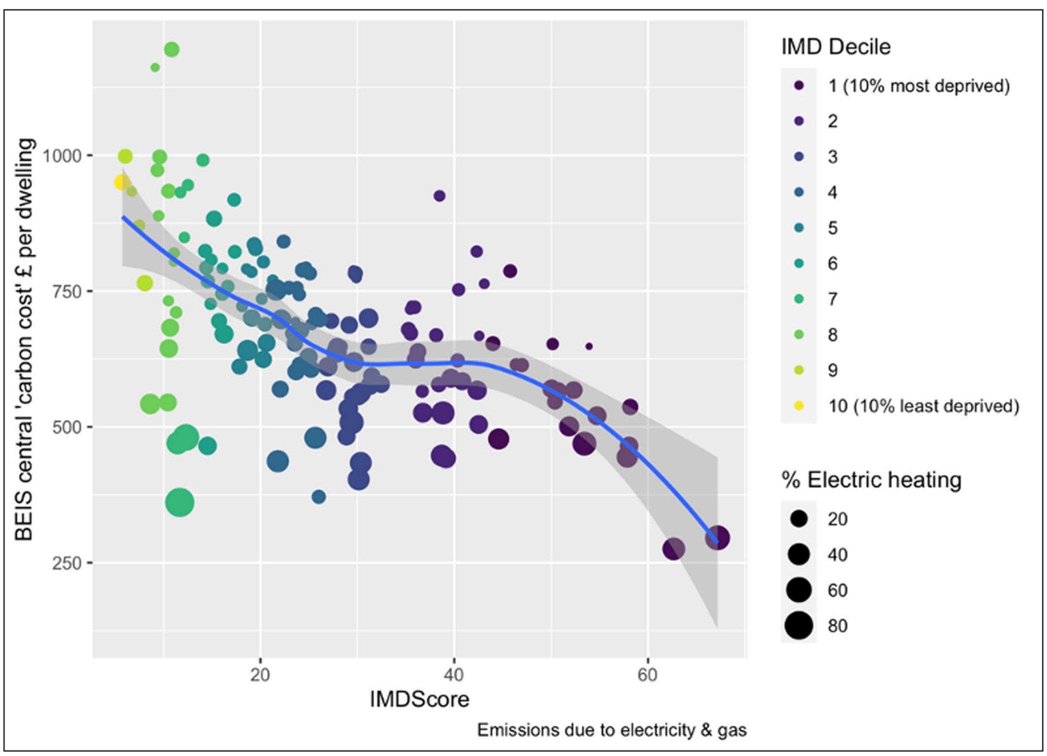

Figure 7: Lower layer super output area (LSOA) level per dwelling carbon 'levy' for 'gas and electricity emissions' against the 2019 Index of Multiple Deprivation (IMD) score.

Notes: Coloured by the score decile, the size of the point represents the proportion of electric heating. The smoothed line is fitted using locally estimated scatterplot smoothing (LOESS) (Wickham 2016).

For comparison, Figure 7 combines the gas- and electricity-use emissions levy and additionally uses the size of the point to indicate the prevalence of electric heating in the LSOA. In this case a similar negative linear relationship between emissions and deprivation at the LSOA level is clear as

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is the order of magnitude reduction in the emissions levy when all other consumption emissions are excluded. However, it is noticeable that several less deprived areas have much lower emissions (and thus lower emissions levy) due to the higher prevalence of electric heating as recorded in 2011.

Comparing these plots with Figure 5 suggests that the higher emitting areas, which tend to be less deprived, will require the least retrofit investment in capital cost terms. Conversely the least emitting areas, which tend to be more deprived, will need substantially more capital investment in retrofit. It is likely therefore that a hypothecated emissions levy will need to transfer revenue from higher emitting, less deprived areas to lower emitting, more deprived areas.

4.1.2 Making it pay (off)

Figure 8 shows the number of years it would take to cover the estimated bands D–G retrofit costs in each LSOA if 100% of the 'all consumption emissions' levy were to be re-invested locally rather than pooled and redistributed. Although this is an unlikely situation it serves to illustrate the spatial heterogeneity in both levy revenue and capital investment costs required. Further, the plot ignores the probable decrease in emissions and thus decrease in carbon costs and levy value as retrofitting takes place. As a result, it is not intended to accurately represent the actual years of levy required but to illustrate that many less deprived areas would cover their costs within a few years due to their high emissions levels and relatively low retrofit costs. In contrast, many deprived areas would take considerably longer, with some areas taking up to 10 years. There is therefore clearly a case for 'levelling up' or transferring the levy from highly emitting and/or lower retrofit cost areas to lower emitting, higher cost and more deprived areas.

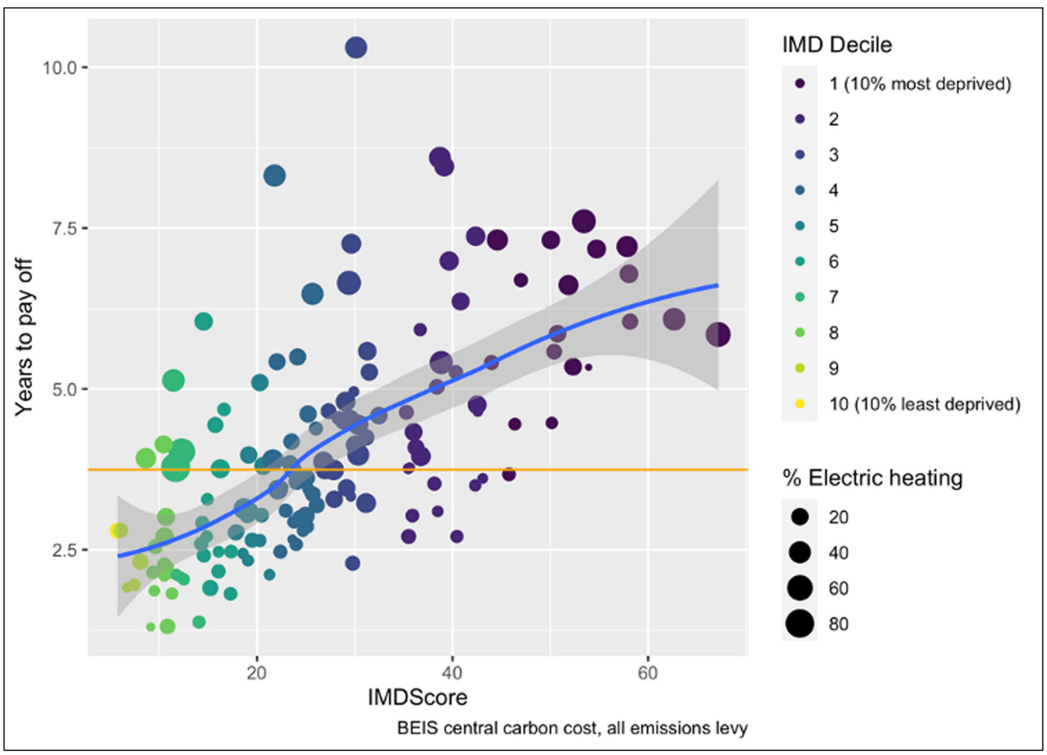

Figure 8: Years required to cover the estimated retrofit costs for each lower layer super output area (LSOA) using an 'all consumption emissions' carbon levy—assuming a constant levy value.

Notes: A median value of 3.7 years is plotted. The smoothed line is fitted using locally estimated scatterplot smoothing (LOESS) (Wickham 2016).

If the levy were instead to be based on energy use (gas and electricity emissions) then the years required would be substantially higher at 10–20 for less deprived higher emitting areas and up to 60 for lower emitting and less energy-efficient areas. Given this elongated time frame the rest of the paper only discusses an 'all consumption emissions'-based levy since it appears to be able to deliver the required capital in the necessary time frame, at least as modelled here.

4.1.3 Making it pay (off) equitably

Figure 9 shows the effect of reinvesting the estimated carbon levy for 'all consumption emissions' into retrofitting bands D–G dwellings equally in each LSOA after one year. The plot shows that two LSOAs in Bargate and one in Swaythling have already 'made it over the line' because their retrofit costs are low. Others are approaching 'pay-off', while a few have several more years to go, notably in one Bevois LSOA (E01017154) where 32% of dwellings were estimated to be in bands F and G with a further 43% in bands D and E.

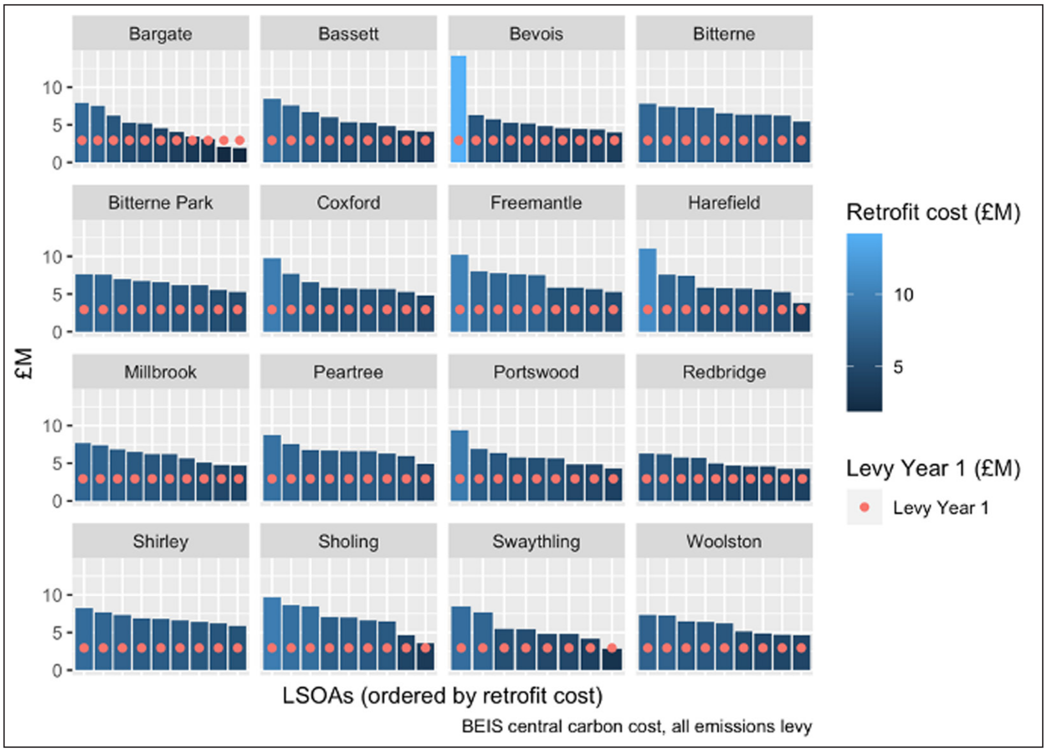

Figure 9: Lower layer super output area (LSOA)-level total bands D–G retrofit costs against equally shared year 1 total consumption emissions-based carbon cost levy.

Note: LSOAs are ordered by total retrofit costs within wards.

4.2 SCENARIO 2: RISING BLOCK CARBON VALUE

The total levy value for the 'all consumption' residential emissions for Southampton under Scenario 2 was £323 million in year 1, considerably lower than the £453 million under Scenario 1. This was also the case for emissions due to gas (£31 million) and due to electricity (£16 million).

Table 7 replicates Table 6 but shows the results for the rising block tariff. As intended, the per dwelling levy for the highest emitting areas is now higher than it was under Scenario 1, but has roughly halved for the least emitting areas.

Table 7: Highest and lowest lower layer super output area (LSOA)-level emissions and carbon costs per dwelling by source (rising block tariff)

Note: IMD = Index of Multiple Deprivation.

EMISSIONS SOURCE	LSOA	DEPRIVATION (IMD) DECILE	WARD	tCO_2e PER DWELLING PER YEAR	CARBON COST PER DWELLING PER YEAR (£)	ESTIMATED TOTAL ANNUAL HOUSEHOLD INCOME (£)	% OF ESTIMATED ANNUAL INCOME
All consumption	E01017249	8	Shirley	44.96	£13,148	£58,400	22.5%
	E01017140	3	Bargate	5.80	£713	£34,100	2.1%
Gas use	E01017249	8	Shirley	3.66	£965	£58,400	1.7%
	E01032746	7	Bargate	0.01	£1	£40,800	0.0%
Electricity use	E01032746	7	Bargate	1.46	£313	£40,800	0.8%
	E01017278	4	Woolston	0.66	£80	£34,100	0.2%

It was intended that Scenario 2 would be more progressive than Scenario 1, and this is confirmed by Figure 10 that shows the total LSOA level revenue that would flow from the 'all consumption' emission levy under the two scenarios. However, while the rising block tariff under Scenario 2 clearly reduces the contribution from higher deprivation and low emissions areas, with the exception of a few outliers it fails to counterbalance this with a substantially higher contribution from the less deprived, higher emitting areas.

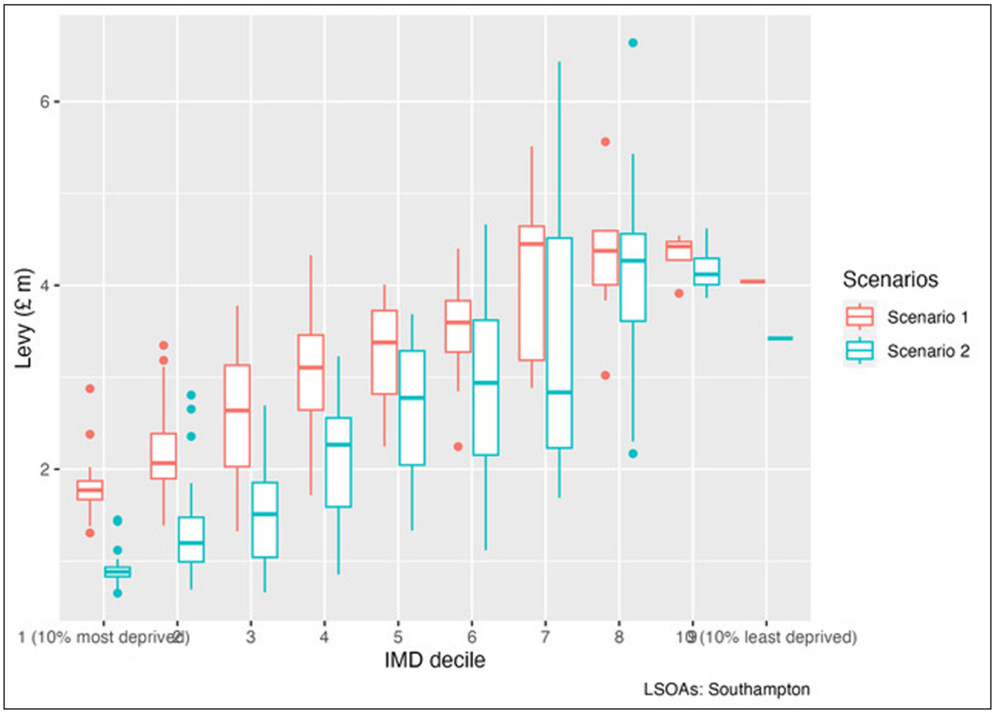

Figure 10: Costs (£ millions) per lower layer super output area (LSOA) for 'all consumption'-based emissions levy by Index of Multiple Deprivation (IMD) decile under each scenario.

While distribution of the levy under this scenario has clearly changed, the distribution of retrofit costs has not. Therefore, an adjustment is needed to the number of years it would take particular areas to cover their retrofit costs under Scenario 2 and this is driven by their level of emissions. This is evident from Figure 11 which compares the years to pay-off for Scenario 1 (*x*-axis) and Scenario 2 (*y*-axis). As indicated previously, the areas that would cover their retrofit costs quickly are less deprived, higher emitting areas. In some areas at the extreme lower left this would happen quicker than under Scenario 1 (they are marginally below the $x = y$ line) due to the increased levy raised from higher emitters via the rising block approach. However, for lower emitting and generally more deprived areas, the time to pay-off would be substantially longer under Scenario 2 due to the decrease in levy revenue from lower emissions areas. In the most extreme case, the pay-off time doubles from 10 to 20 years.

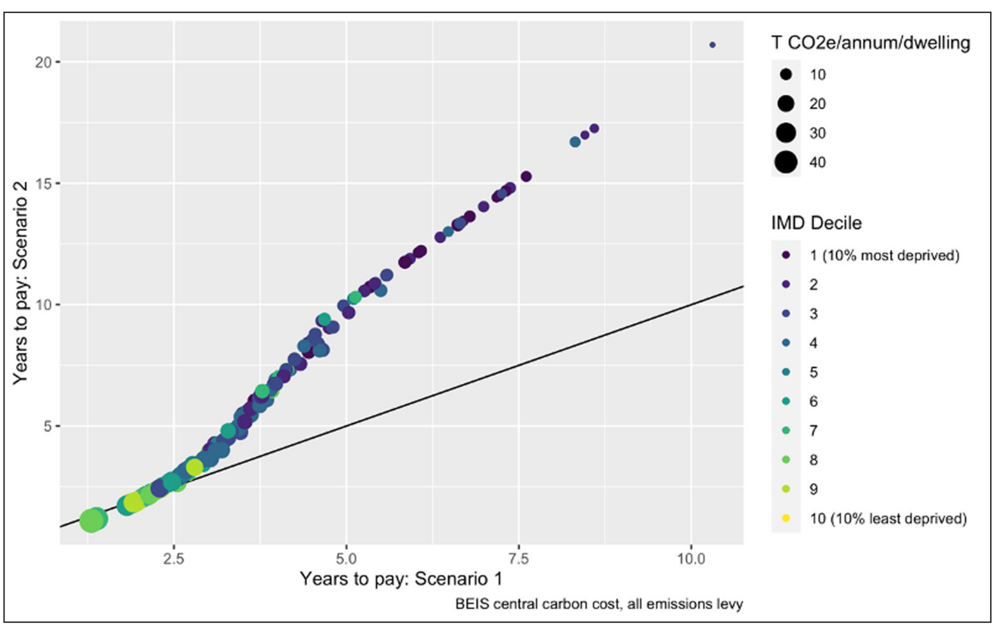

Figure 11: Years required to cover the estimated retrofit costs for each lower layer super output area (LSOA) under each scenario using an 'all consumption emissions' carbon levy—assuming a constant levy value.

Note: The $x = y$ line is plotted.

5. DISCUSSION

The results of the retrofit cost estimations suggest that as of 2018, the cost of upgrading all EPC bands D–G dwellings in Southampton to at least band C was about £908 million and the majority of this cost would be incurred in areas of higher deprivation (Figure 5). Due to the use of area-level data it is not possible to disaggregate these costs to the owner–occupier versus social versus private rented building stock, but the prevalence of low-quality housing in areas with a high proportion of private rentals (Figure 3) suggests that these areas would also incur a significant proportion of the costs. This is also likely to be the case for areas with high proportions of social renters, although the effect is not as concentrated. Given the lower 'ability to pay' and the higher rates of rental for households in these areas, this would argue for the use of funding raised through a form of emissions levy to directly fund energy efficiency retrofits in these areas. In the case of social rentals, and those in energy poverty, current UK government programmes are likely to provide this funding, albeit at currently lower than required rates (Climate Change Committee 2023). However, in the case of private rentals this level of retrofit relies on landlords responding to minimum energy performance regulations for rental properties in the D–G bands.

The results of the scenarios suggest that a hypothecated carbon emissions levy *could* fund investment in energy-efficient retrofit of the existing building stock within a reasonable time frame, but only if it were charged at 100% of the £245/tCO_2 carbon value and if it were applied to 'all consumption'-based rather than purely residential energy-based emissions. This is the case under either a fixed multiplier (Scenario 1) or rising block (Scenario 2) approach, but with very different estimated 'years to pay'.

Under Scenario 1, which used the BEIS central carbon value, the median number of years it would take for Southampton LSOAs to cover 'their' retrofit costs would be 3.7, with some LSOAs 'crossing the line' well in advance of this but others needing 10 years or more. This clearly shows that the value of the levy generated by local areas in the case study area of Southampton under Scenario 1 would exhibit considerable spatial variation due to spatial heterogeneity in emissions levels (Figures 5 and 10). At the area level, low emissions correlates strongly with higher deprivation especially when 'all consumption' emissions are considered. As a result, areas that are high emitters and generally less deprived would generate high levels of levy compared with more deprived and lower emitting areas. However, the latter tend to have much higher estimated retrofit investment costs due to the prevalence of energy inefficient dwellings. If significant inequity in the scale and rate of retrofitting at the small area level is to be avoided, it would be crucial to redistribute the levy funds from high emissions neighbourhoods to low emissions ones where significant retrofit is required.

Applying the levy at lower rates of carbon value (Table 1) or only to energy-derived emissions (Table 2) would significantly reduce the value of the levy that could be generated. This would substantially extend the number of years that would be required for the local levy to pay for the required retrofit investments, especially if the effect of the investments themselves was to subsequently lower the emissions-driven levy that could be generated. In the most extreme case, the pay-off time doubles from 10 to 20 years. These findings align with previous work on the potential utility of an energy-use-based carbon tax to fund energy efficiency programmes, which suggests that even a relatively high carbon tax rate would not necessarily ensure that medium-to-deep retrofits would be economically viable (Royapoor *et al.* 2019; Freyre *et al.* 2020).

As implemented in this paper, the rising block tariff (Scenario 2) would have the desired effect of reducing the levy 'burden' for lower emitting and more deprived areas (Figure 10). However, the multipliers used do not adequately compensate for the reduced low emissions carbon value so that overall levy revenue is lower than under Scenario 1. The consequence of this is that the overall and per area pay-off period would generally be longer (Figure 11). In the most extreme case, the pay-off time doubles from 10 to 20 years. The finding that this elongation would most severely effect areas of higher relative deprivation (Figure 11) not only confirms the need for the redistribution of funds within the areas but also shows that a more punitive rising block tariff multiplier, or shift in tariff thresholds, would be required to achieve the same overall levy value as under Scenario 1.

Manipulating cost multipliers could also be used to increase the proportion of the levy flowing from energy sources (such as gas) that need to be reduced. While this would be a natural consequence of the ongoing decarbonisation of the electricity grid, the levy could be used to provide additional incentives to switch to low emissions energy sources by increasing the 'carbon cost' of gas per tCO_2 emitted compared with electricity.

6. CONCLUSIONS

This paper has used area-level emissions estimates combined with other data sources to demonstrate that a household-level emissions levy using 100% of current projected carbon value *could* be hypothecated to fund local area retrofit programmes. This is the case whether the levy is calculated against estimates of 'all consumption' emissions or energy use. However, as the latter are substantially lower than the former, using a levy applied to just energy emissions would, in the absence of an additional carbon value multiplier, not provide sufficient funds over the timescales required to reduce energy demand and emissions in line with net zero goals.

In general, the levy revenue from less deprived areas which are usually higher emitters would be larger and would quite quickly (within two to three years) fund area-level retrofit costs if reinvested only within those areas and if revenue levels remained constant. This is not the case for more deprived, generally lower emitting areas (lower levy) that tend to require larger retrofit capital investment. This means that a significant redistribution of the levy would be required to ensure the implementation of an equitable and net zero effective energy efficiency retrofit programme.

The paper tested two approaches to levy calculation: a simple multiplier of the central carbon value (Scenario 1) and a rising block tariff approach (Scenario 2). The overall results are largely the same for the two approaches, but as implemented here, Scenario 2 raises substantially less revenue, especially from lower emitting, more deprived areas. This is an intended consequence of a progressive rising block approach, but it is likely that the 'high emissions' multiplier would need to be substantially larger than 1.5 times the central carbon cost (as now) (Table 4) to be effective.

Naturally, in the long run such a system is unsustainable. Just as vehicle excise linked to internal combustion engine emissions will generate less and less revenue over time as engines become lower emitters or vehicle switch to electric power, so it could be anticipated that a local carbon levy would also tend to zero as retrofit investments are made (Royapoor *et al.* 2019). This has not been modelled in the 'years to pay off' analysis in this paper and would require a more sophisticated model of retrofit progress and emissions reductions consequences. This is left to future research.

Clearly this approach would have numerous challenges, not least to implementation. For example, as noted above the rate of retrofit and carbon value would need to be managed to ensure that the 'remaining emissions' can always balance the 'remaining retrofit' costs. More crucially, the practical feasibility of collecting an emissions levy on 'all consumption' items for members of a given dwelling, where the majority of non-measured energy emissions are likely to be due to transport, needs to be considered. It is therefore unclear how an emissions levy could be estimated and collected if not on measured consumption (*i.e.* energy and fuels, as in Murray & Rivers 2015) and how it could be structured to avoid unintended consequences. Future research could assess the additional revenue that could be raised under an 'energy emissions' levy if measurable and spatially allocatable transport-related emissions were included. Future iterations of the model reported in this paper could then indicate whether a levy applied to in-home and transport energy use would generate similar levels of funding. This would then give the opportunity to apply more punitive carbon costs to fuel sources which are considered incompatible with net zero ambitions.

From a system perspective, wealthier high emitters might use private capital to reduce emissions more rapidly, leading to a faster-than-expected drop in emissions levy revenue. On the other hand, tenants and lease-holders would generally be liable for a levy based on a set of circumstances over which they may have little control. Landlords, in contrast, may have little incentive to invest (Ambrose 2015; März 2018). These challenges are well known in the energy efficiency and retrofit literature and recent work suggests that mandating the sharing of benefits between landlords and tenants may provide a solution (Freyre *et al.* 2020; Cremer & Weber 2022). Given the high proportion of private renters in the City of Southampton, and especially those likely to be students living in lower quality housing, these results could be significant, although they require clear policy and regulatory action to implement.

Clearly individual households are unlikely to accept an emissions levy that does not take account of actions they have taken to decarbonise the energy sources they still use. From an emissions estimation point of view, the method would therefore need to account for 'renewable electricity' or other similar tariff choices which in theory would set some emissions categories to close to zero, thus reducing the levy that could be generated from these sources.

From a methodological point of view, it should also be noted that the Energy Performance Certificate (EPC) data used are likely to become rapidly outdated as upgrades continue. In addition, the estimates of retrofit costs, and in particular the prevalence of low energy efficiency dwellings in the areas in the case study, may be erroneous due to known EPC inaccuracies, non-random coverage as well as change over time.

Finally, this analysis has used area-level data to simulate the application of a dwelling-level emissions levy. In doing so it relies on estimates of mean emissions per dwelling at the area (lower layer super output area—LSOA) level and so runs the risk of ecological fallacy effects (Openshaw 1984). It is also unable to examine the distributional effects of such a levy at the household level which would be crucial to understanding its equity consequences and should be the focus of future research.

In summary, this paper shows that a local area carbon levy on residential emissions would not self-fund energy efficiency upgrades in the City of Southampton's dwelling stock 'to a reasonable standard' within an acceptable time frame. It would only be effective in high emissions areas and the levy would need to be redistributed to lower emissions (and thus lower levy-generating) areas which also tend to be those with the highest energy poverty and the worst housing. Even then, a relatively punitive level of carbon taxation would be required.

In common with other work modelling retrofit in specific buildings (Royapoor *et al.* 2019) or for larger programmes (Freyre *et al.* 2020), this paper is therefore evidence of the need for public investment above and beyond that which could be raised by a local carbon levy to ensure energy efficiency upgrades occur within a reasonable time frame for those in greatest need. It also implies that innovation in financial models is required to ensure that the rate of upgrade, and thus decrease in energy use, emissions and energy insecurity is accelerated across middle-to-high emitters who are unlikely to receive direct government support, where their own capital is insufficient and their incentives to invest are relatively low. Emerging research suggesting that energy efficiency improvements are increasingly valued at future resale indicates that debt- or mortgage-based finance repaid at resale could be one such alternative (Adan & Fuerst 2016; Aydin *et al.* 2020).

NOTES

1 See also https://www.carbon.place/data/.

2 See https://www.gov.uk/government/statistics/uks-carbon-footprint/.

3 See https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/earningsandworkinghours/datasets/smallareaincomeestimatesformiddlelayersuperoutputareasenglandandwales/.

4 See https://epc.opendatacommunities.org/.

5 See https://www.ons.gov.uk/peoplepopulationandcommunity/personalandhouseholdfinances/incomeandwealth/bulletins/smallareamodelbasedincomeestimates/financialyearending2018#income-estimates-for-small-areas-data/.

6 Estimates of the number of students in UK university cities in 2021 are likely to be lower than expected due to COVID lockdown arrangements, which meant they were likely to be enumerated at their home address.

7 See https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/earningsandworkinghours/datasets/smallareaincomeestimatesformiddlelayersuperoutputareasenglandandwales/.

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COMPETING INTERESTS

The author has no competing interests to declare.

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REFERENCES

Adan, H., & **Fuerst, F.** (2016). Do energy efficiency measures really reduce household energy consumption? A difference-in-difference analysis. *Energy Efficiency*, 9, 1207–1219. DOI: https://doi.org/10.1016/j.future.2018.04.078

Ambrose, A. R. (2015). Improving energy efficiency in private rented housing: Why don’t landlords act? *Indoor and Built Environment*, 24(7), 913–924. DOI: https://doi.org/10.1177/1420326X15598821

Andersson, J. J. (2019). Carbon taxes and CO_2 emissions: Sweden as a case study. *American Economic Journal: Economic Policy*, 11(4), 1–30. DOI: https://doi.org/10.1257/pol.20170144

Aydin, E., Brounen, D., & **Kok, N.** (2020). The capitalization of energy efficiency: Evidence from the housing market. *Journal of Urban Economics*, 117(May), 103243. DOI: https://doi.org/10.1016/j.jue.2020.103243

BEIS. (2021a). *Valuation of greenhouse gas emissions: For policy appraisal and evaluation*. Department for Business, Energy and Industrial Strategy (BEIS). https://www.gov.uk/government/publications/valuing-greenhouse-gas-emissions-in-policy-appraisal/valuation-of-greenhouse-gas-emissions-for-policy-appraisal-and-evaluation

BEIS. (2021b). *Plan to drive down the cost of clean heat*. Department for Business, Energy and Industrial Strategy (BEIS). https://www.gov.uk/government/news/plan-to-drive-down-the-cost-of-clean-heat

BEIS. (2022). *British energy security strategy* (7 April). Department for Business, Energy and Industrial Strategy (BEIS). https://www.gov.uk/government/publications/british-energy-security-strategy/british-energy-security-strategy

Berry, A. (2019). The distributional effects of a carbon tax and its impact on fuel poverty: A microsimulation study in the French context. *Energy Policy* 124: 81–94. DOI: https://doi.org/10.1016/j.enpol.2018.09.021

Braungardt, S., Tezak, B., Rosenow, J., & **Bürger, V.** (2023). Banning boilers: An analysis of existing regulations to phase out fossil fuel heating in the EU. *Renewable and Sustainable Energy Reviews*, 183(September), 113442. DOI: https://doi.org/10.1016/j.rser.2023.113442

Büchs, M., Bardsley, N., & **Duwe, S.** (2011). Who bears the brunt? Distributional effects of climate change mitigation policies. *Critical Social Policy*, 31(2), 285–307. DOI: https://doi.org/10.1177/0261018310396036

Büchs, M., & **Schnepf, S. V.** (2013). Who emits most? Associations between socio-economic factors and UK households' home energy, transport, indirect and total CO_2 emissions. *Ecological Economics*, 90 (June), 114–123. DOI: https://doi.org/10.1016/j.ecolecon.2013.03.007

Chisholm, E., Keall, M., Bennett, J., Marshall, A., Telfar-Barnard, L., Thornley, L., & **Howden-Chapman, P.** (2019). Why don't owners improve their homes? Results from a survey following a housing warrant-of-fitness assessment for health and safety. *Australian and New Zealand Journal of Public Health*. DOI: https://doi.org/10.1111/1753-6405.12895

Climate Change Committee. (2020). *Sixth carbon budget*. https://www.theccc.org.uk/publication/sixth-carbon-budget/

Climate Change Committee. (2023). *Progress in reducing emissions: 2023 Report to Parliament*. https://www.theccc.org.uk/publication/2023-progress-report-to-parliament/

Crawley, J., Biddulph, P., Northrop, P. J., Wingfield, J., Oreszczyn, T., & **Elwell, C.** (2019). Quantifying the measurement error on England and Wales EPC ratings. *Energies*, 12(18), 3523. DOI: https://doi.org/10.3390/en12183523

Cremer, L., & **Weber, C.** (2022). Deep energy retrofits: How effective and robust are policy instruments? *Energy Policy*, 170, 113210. DOI: https://doi.org/10.1016/j.enpol.2022.113210

DESNZ. (2023). *Sub-national methodology and guidance 2023*. Department for Energy Security and Net Zero (DESNZ). https://www.gov.uk/government/publications/regional-energy-data-guidance-note

Druckman, A., Buck, I., Hayward, B., & **Jackson, T.** (2012). Time, gender and carbon: A study of the carbon implications of British adults' use of time. *Ecological Economics*, 84, 153–163. DOI: https://doi.org/10.1016/j.ecolecon.2012.09.008

Economidou, M., Todeschi, V., Bertoldi, P., D'Agostino, D., Zangheri, P., & **Castellazzi, L.** (2020). Review of 50 years of EU energy efficiency policies for buildings. *Energy and Buildings*, 225(October), 110322. DOI: https://doi.org/10.1016/j.enbuild.2020.110322

Faiella, I., & **Lavecchia, L.** (2021). Energy poverty. How can you fight it, if you can't measure it? *Energy and Buildings*, 233(February), 110692. DOI: https://doi.org/10.1016/j.enbuild.2020.110692

Fleurbaey, M., Ferranna, M., Budolfson, M., Dennig, F., Mintz-Woo, K., Socolow, R., Spears, D., & **Zuber, S.** (2019). The social cost of carbon: Valuing inequality, risk, and population for climate policy. *The Monist*, 102(1), 84–109. DOI: https://doi.org/10.1093/monist/ony023

Freyre, A., Klinke, S., & **Patel, M. K.** (2020). Carbon tax and energy programs for buildings: Rivals or allies? *Energy Policy*, 139, 111218. DOI: https://doi.org/10.1016/j.enpol.2019.111218

Friedler, C., & **Kumar, C.** (2019). *Reinventing retrofit: How to scale up home energy efficiency in the UK*. Green Alliance.

Ghaith, A. F., & **Epplin, F. M.** (2017). Consequences of a carbon tax on household electricity use and cost, carbon emissions, and economics of household solar and wind. *Energy Economics*, 67(September), 159–168. DOI: https://doi.org/10.1016/j.eneco.2017.08.012

HM Revenue & Customs and HM Treasury. (2021). *Carbon emissions tax: Summary of responses to the consultation* (23 March). https://www.gov.uk/government/consultations/carbon-emissions-tax

Jenkins, D., Simpson, S., & **Peacock, A.** (2017). Investigating the consistency and quality of EPC ratings and assessments. *Energy*, 138(November), 480–489. DOI: https://doi.org/10.1016/j.energy.2017.07.105

Lord Deben. (2022). *Reducing energy demand in buildings in response to the energy price crisis* (9 November). Climate Change Committee. https://www.theccc.org.uk/publication/letter-reducing-energy-demand-in-buildings-in-response-to-the-energy-price-crisis/

März, S. (2018). Beyond economics—Understanding the decision-making of German small private landlords in terms of energy efficiency investment. *Energy Efficiency*, 11(7), 1721–1743. DOI: https://doi.org/10.1007/s12053-017-9567-7

MHCLG. (2018). *English Housing Survey 2018: Energy report*. Ministry of Housing, Communities & Local Government (MHCLG). https://www.gov.uk/government/statistics/english-housing-survey-2018-energy-report

MHCLG. (2019). *The English Indices of Deprivation 2019 (IoD2019)*. Ministry of Housing, Communities & Local Government (MHCLG). https://www.gov.uk/government/statistics/english-indices-of-deprivation-2019

Mohareb, E., Gillich, A., & **Bristow, D.** (2022). Participation in domestic energy retrofit programmes: Key spatio-temporal drivers. *Buildings & Cities*, 3(1), 356–375. DOI: https://doi.org/10.5334/bc.202

Morgan, J., Chu, C. M., & **Haines-Doran, T.** (2023). Competent retrofitting policy and inflation resilience: The cheapest energy is that which you don't use. *Energy Economics*, 121(May), 106648. DOI: https://doi.org/10.1016/j.eneco.2023.106648

Morgan, M., Anable, J., & **Lucas, K.** (2021). A place-based carbon calculator for England. *Paper presented at the 29th Annual GIS Research UK Conference (GISRUK)*, Cardiff, UK, 6 April. DOI: https://doi.org/10.5281/zenodo.4665852

Murray, B., & **Rivers, N.** (2015). British Columbia's revenue-neutral carbon tax: A review of the latest 'grand experiment' in environmental policy. *Energy Policy*, 86(November), 674–683. DOI: https://doi.org/10.1016/j.enpol.2015.08.011

Ofgem. (2015). *Energy spend as a percentage of total household expenditure (UK)* (8 June). https://www.ofgem.gov.uk/data-portal/energy-spend-percentage-total-household-expenditure-uk

Openshaw, S. (1984). Ecological fallacies and the analysis of areal census data. *Environment and Planning A*, 16(1), 17–31. DOI: https://doi.org/10.1068/a160017

Piddington, J., Nicol, S., Garrett, H., & **Custard, M.** (2020). *The housing stock of the United Kingdom*. BRE Trust.

Raslan, R., Schwartz, Y., & **Symonds, P.** (2020). *Analysis work to refine fabric energy efficiency assumptions for use in developing the Sixth Carbon Budget*. https://discovery.ucl.ac.uk/id/eprint/10117186/

Royapoor, M., Du, H., Wade, N., Goldstein, M., Roskilly, T., Taylor, P., & **Walker, S.** (2019). Carbon mitigation unit costs of building retrofits and the scope for carbon tax, a case study. *Energy and Buildings*, 203, 109415. DOI: https://doi.org/10.1016/j.enbuild.2019.109415

Wang, Q., Hubacek, K., Feng, K., Wei, Y.-M., & **Liang, Q.-M.** (2016). Distributional effects of carbon taxation. *Applied Energy*, 184(December), 1123–1131. DOI: https://doi.org/10.1016/j.apenergy.2016.06.083

Wickham, H. (2016). *ggplot2: Elegant graphics for data analysis*. Springer. DOI: https://doi.org/10.2307/2289282

Zangheri, P., Castellazzi, L., d'Agostino, D., Economidou, M., Ruggieri, G., Tsemekidi-Tzeiranaki, S., Maduta, C., & **Bertoldi, P.** (2021). *Progress of the member states in implementing the Energy Performance of Building Directive* (JRC Publications Repository, 2 August). DOI: https://doi.org/10.2760/914310

Zetland, D., & **Gasson, C.** (2013). A global survey of urban water tariffs: Are they sustainable, efficient and fair? *International Journal of Water Resources Development*, 29(3), 327–342. DOI: https://doi.org/10.1080/07900627.2012.721672

Zhang, Z., Zhang, A., Wang, D., Li, A., & **Song, H.** (2017). How to improve the performance of carbon tax in China? *Journal of Cleaner Production*, 142, 2060–2072. DOI: https://doi.org/10.1016/j.jclepro.2016.11.078

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