



Can different approaches to funding household energy efficiency deliver on economic and social policy objectives? ECO and alternatives in the UK

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ARTICLE INFO

JEL classification:

C68
Q43
Q48

Keywords:

Energy efficiency
Energy policy
Economic sustainability
Socialising costs
Computable general equilibrium

ABSTRACT

Residential energy efficiency is a core element of the decarbonisation policy in many nations. In the UK, the established approach to enabling efficiency gains through centralised retrofitting programmes involves socialising costs via consumer energy bills through the Energy Company Obligation (ECO). One UK policy concern is whether less affluent households should receive greater access to ECO funding. However, there is a broader concern that the use of constrained public resources should be justified through wider and sustained economic returns emerging. Here, we consider the (centralised) ECO approach to cost recovery alongside alternative (decentralised) approaches to delivering energy efficiency programmes that either pass costs to beneficiary households or fully socialise costs via income tax. We find the key drivers of both household and wider economy outcomes are the absolute levels of resources actually devoted to enabling efficiency gains and household disposable income freed up to power expansionary processes. The latter in particular brings challenges and trade-offs in terms of meeting both economic performance and social policy objectives, given that resources targeted at higher income households can ultimately free up more real spending ability and sustain greater gains in GDP, employment and household incomes.

1. Introduction

Since the 2015 Paris Agreement (UNFCCC, 2015) a number of countries have introduced strategies and measures to achieve the agreed goals. At different governance levels (e.g. European Union, UK and Scotland), energy efficiency improvement policies are a key component of climate change mitigation efforts. Moreover, given that the potential wider benefits of energy efficiency improvements have been well documented by organisations like the International Energy Agency (IEA, 2014), policymakers are increasingly recognising that energy efficiency actions can attract wider public policy support through the potential to deliver returns across a wide range of policy objectives. In the UK national and Scottish devolved context, recent policy actions have focussed on residential energy efficiency programmes, treated as potential economic mechanisms for combining the delivery of emissions reductions

with economic stimuli¹ and addressing social challenges such as fuel poverty.² The ability of energy efficiency enhancing actions to deliver sustained wider economy expansions has also been the focus of much attention in the academic literature, most commonly in the context of trading off potential erosions in, or 'rebound effects', against technically possible energy savings and emissions reductions (see review in Section 2).

However, retrofitting a property to improve its energy efficiency often embodies significant upfront costs for the property owners with the implication that some time may pass before cost recovery, energy savings and boosted real spending power can be realised. This may motivate policy action to support households in covering and/or financing part or the entire cost of the retrofitting required to deliver energy efficiency gains. For example, in the UK – or more specifically Great Britain³ – the most commonly used approach to date has been the

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¹ In July 2020, the UK Chancellor of the Exchequer announced the introduction of Green Grants in England to support energy efficiency improvements as part of a post-Covid economic stimulus package. See <https://www.bbc.co.uk/news/business-53313640> for reporting of announcement and <https://greenhomesgrant.campaign.gov.uk/> for rollout.

² The devolved Scottish Government have given more explicit attention to the combined role of residential energy efficiency actions in addressing fuel poverty challenges alongside emissions reduction and economic expansion. See Scottish Government (2018).

³ Great Britain is defined as the mainland UK area encompassing England, Wales and Scotland but not Northern Ireland.

Energy Company Obligation (ECO). Under ECO, the major energy suppliers⁴ have to meet specific targets set by the energy market regulator, Ofgem, with this involving the support of centralised energy efficiency improvement programmes. A key downside of ECO is that it involves significant administrative costs and other implementation costs that restrict the share of the available ECO budget actually directed to retrofitting properties. It has also been argued – for example in a high profile UKERC study (Barrett et al., 2018) – that, by recovering costs through the energy bills of all consumers, ECO places a disproportionate burden on lower income households, thereby raising questions around whether ECO is the most effective funding mechanism.

Thus, questions arise as to whether alternative approaches that socialise costs in a more progressive way and shift away from the centralised support of energy efficiency improvements (as ECO may be characterised) towards households sourcing their own retrofitters, potentially with support via low/zero interest loans, may achieve better outcomes at the same or even reduced costs. This provides the focus and scope for the current study. We investigate the comparative household and wider economy costs and benefits of ECO and alternative approaches to support the delivery of residential energy efficiency improvements in the UK. We do so by adopting a computable general equilibrium (CGE) modelling approach to identify how three alternative funding options support residential efficiency improvements and deliver a range of efficiency and wider economy gains. We analyse the impacts in different timeframes, with a view to gain a better understanding of the transmission mechanisms driving the qualitative nature of these impacts and their potential absolute and relative magnitudes, rather than to forecast actual likely outcomes. We also direct particular attention to how outcomes and implications may change a) if the expected efficiency gains do not materialise and b) if access to funds is distributed equally across all households or using a tapered approach which provides access to more funds to less affluent households.

Our analyses show that it is not possible to identify a single combination of funding mechanism and access distribution that could potentially deliver the best economy-wide outcomes and greatest income boost to the lowest income households (and avoid net losses in all timeframes where efficiency gains are not fully realised). Ultimately, the ‘best’ combination of outcomes will of course depend on the specific objectives of the proposed energy efficiency policy action and a key aim of this work is to demonstrate how information to inform policy decisions can be generated through an economy-wide analysis of the type set out here. The rest of the paper is structured as follows. Section 2 considers the gap in the existing literature on energy efficiency and economy-wide impacts addressed by our contribution. Section 3 sets out our scenario simulation strategy and the key characteristics of our analytical approach. In Section 4, we then present and discuss the key findings of our analyses, before summarising the main insights and policy implications in the concluding Section 5.

2. The existing literature on the wider economy impacts of energy efficiency

The impact of residential energy efficiency improvements has been extensively researched from a variety of perspectives (e.g. Figus et al., 2017; Moglia et al., 2017; Geels et al., 2018; Laes et al., 2018). Many socio-economic studies have focussed on the impacts of actually realising efficiency gains, and specifically on issues such as rebound effects in energy demand as economic gains emerge (Sorrell, 2007; Turner, 2013). This focus on performance (particularly under the common assumption of costless and exogenous efficiency improvements) overlooks the

⁴ According to the Ofgem, the Great Britain energy market regulator, energy suppliers with more than 150,000 domestic customers and supplying over 300 GWh of electricity or 700 GWh of natural gas, have legal obligations under ECO.

interacting and potentially offsetting impacts of what is required to actually enable efficiency actions. In practice, the conduct and funding of retrofitting activities will both in itself have near term socio-economic impacts and influence the magnitude of the achievable efficiency gains that ultimately deliver sustained outcomes for households and the wider economy (Gillingham et al., 2016).

In the limited number of studies that do give attention to the presence of costs (if not the process) in enabling efficiency improvements, a range of analytical approaches can be observed. For example, some studies simply adjust modelling parameters to reflect the presence of a capital cost in implementing efficiency improvements (Henly et al., 1988; Mizobuchi, 2008). Others consider the cost of efficiency improvements in terms of closing an ‘energy efficiency gap’, defined as the difference between the cost-minimising energy efficiency levels and the currently achieved energy efficiency (Gillingham and Palmer, 2014; Fowlie et al., 2015; Gerarden et al., 2015; Sathitbun-anan and Fungtammasan, 2015; Trianni et al., 2016). Generally, the underlying assumption in such treatments is that the upfront cost constitutes a barrier to the implementation of efficiency improvements, which motivates treatment of cost via adjustment in the adoption rates (Greening et al., 2000; Sorrell and Dimitropoulos, 2007) rather than explicitly considering the activities that give rise to costs in different timeframes. Thus, one limitation of such treatments is abstraction from the impacts of those activities in different sectors of the economy, and of the wider economy responses that will be triggered. The same is often true of cost effectiveness or cost-benefit analyses (Winkler et al., 2010; Molina, 2014; Dahlhausen et al., 2015; Mata and Kalagasidis, 2015; Tuominen et al., 2015). A third kind of approach requires costs of delivering efficiency improvements through incorporating ‘bottom-up’ techno-economic information in modelling (Kiuiila and Rutherford, 2013; Fæhn and Isaksen, 2016; Bye et al., 2018). While adding crucial insight, this approach also neglects the impacts of specific enabling actions, including different policy and support mechanisms, and fails to give any consideration to the question of who ultimately meets the cost of actions taken.

Thus, there is an important gap in considering the implementation cost of efficiency improvements (Turner, 2013). A more recent study (Yushchenko and Patel, 2016) explores the GDP and employment impacts of enabling energy efficiency through specific policy programmes, but using a similar input-output economy-wide model that cannot capture any price and income effects. Here we address this and the other gaps identified above by developing a more flexible and theory-consistent general equilibrium approach that enables fuller exploration of the real impacts of energy efficiency programmes on different household income groups and across the wider economy. In particular, we focus on programmes funded through constrained public resources, where there is a need to address how the specific design and operation of actual policy actions impact outcomes at household, sectoral and economy-wide levels.

3. Scenario simulation strategy and underpinning methodology

3.1. Funding scenarios to be simulated

Our aim is to explore the wider economy impacts of enabling and realising energy efficiency gains in the UK household sector via three specific funding mechanisms that can be considered as representative examples of wider approaches to supporting residential energy efficiency actions. Here, the existing UK policy framework, the Energy Company Obligation (ECO), represents a support programme where retrofitting costs are socialised via the energy bills of all UK households; that is, a distribution determined by the size of the energy consumption. The use of interest-free loans represents an approach where the cost is passed on to the direct beneficiaries of energy efficiency improvement actions who, rather than having to pay the full amount in a single lump sum payment, can distribute the cost through multiple years even

beyond the duration of the policy itself. Finally, socialising the cost via the income tax is an example of how the cost of the energy efficiency programme could be distributed across the entire household sector, but in a progressive way related to household incomes and ability to pay. The funds raised by the increased taxation are offered as government-issued grants to households implementing energy efficiency improvement projects, with subsequent returns also socialised as the government balances its budget thereby ultimately recycling revenues raised from the wider economy expansion through future adjustment of income tax rates. Within each case, we also consider the impacts of either evenly distributing access to funds available or tapering the distribution to favour households in the lowest income quintile.

3.1.1. Key assumptions: nature of costs involved in delivering via centralised or decentralised programmes

Our central case is the existing ECO programme currently in operation in the UK. One component of ECO is the amount directly used for retrofitting activities, which is one of the main determinants of the number of households that can be supported by every iteration of ECO and therefore the overall efficiency improvement of the UK household stock. The exact share of the total funds that are directly used for efficiency improvements varies but in our analyses we assume that a minimum of 39% of the total cost of ECO is directly used for efficiency improvements.⁵ The funding available for use in actually retrofitting properties is affected by a range of administration costs but also an 'economic rent' (equating to up to 37% of total ECO costs) that is implicit in the design of the centralised scheme. That is, given that ECO effectively equates to a centralised supply of energy efficiency, there are fixed prices for specific activities. These range from activities necessary to the satisfactory completion of retrofitting projects (e.g. cleaning after a cavity wall insulation) but can also lead to the extraction of large profits by the retrofitters where individual projects can be delivered at a lower cost. To explore the impact of this rent, our analyses includes exploration of two boundary-setting scenarios, one where the full rent is present and the other where no rent is present at all. However, there are non-retrofitting costs that further inflate the cost of ECO. The larger of these is the search costs embodied in ECO. That is, as the energy companies delivering ECO need to find appropriate projects to support, they need to source specialist services to identify such projects. The cost for those services can amount up to 14% of the total cost of ECO, while the last 10% is attributed to administrative costs.

In modelling the loans and income tax scenarios, in the absence of appropriate data to inform scenario development, we make the simplifying assumption that there are no administrative costs,⁶ meaning that the total cost of programmes under those approaches is smaller than ECO. The other key difference is that consumers are responsible to source the most appropriate retrofitters for their projects. The first implication of this is that the costs associated with identifying appropriate projects are no longer applicable. The second implication is that the households are expected to look for those that deliver the best results while minimising the cost. This is reflected in the assumption of no rent extraction. That is, the entire amount spent under either of these approaches is used exclusively for efficiency improvements, with the implication that each has the potential to deliver greater efficiency reductions compared to ECO.

⁵ We acknowledge the support of officials from the UK Government Department for Business, Energy and Industrial Strategy (BEIS) Home and Local Energy Analysis Team in supplying data and advising on the assumptions adopted in this study.

⁶ In practice, this is unlikely to be the case, but in the absence of information to fully specify administrative costs across the decentralised options, we simplify with the acknowledgement that the costs of the central ECO option are likely to negatively impact comparative outcomes.

3.1.2. Scenarios to consider the implementation of the energy efficiency improvement programmes

We follow a common approach across all funding mechanisms. Most of the energy efficiency spending (between 33% and 87% of the total funds available depending on the specific mechanism) is directed towards UK 'Construction' sector, which retrofits properties, while boilers and other heating equipment are purchased from the UK 'Manufacture of fabricated metal products, excluding weapons & ammunition' sector (a 75% share) and imports (25% share).⁷ In both cases, we model the additional retrofitting activity as an exogenous increase in the demand for the output of those sectors. We acknowledge that in either case, specific firms within these sectors will be involved, where production features may not map to the average reflected in the more aggregated sector. However, this is the greatest degree of granularity reported in the UK Input-Output tables that constitute the core element of our CGE model database.

We explore four funding cases in total, with ECO split into 'with rent' and 'without rent' cases. We assume that each one of them is the sole support mechanism of a 16-year energy efficiency improvement programme. On average, data from the National Energy Efficiency Data (NEED) framework suggests each retrofitted property becomes on average 17.2% more energy efficient but we scale the efficiency gains to reflect the efficiency improvement of the each household income quintile as a whole (see Section 3.2). We also explore two approaches in distributing access to funding; one where access is distributed equally to all quintiles and a tapered distribution approach where, from year 6 onwards, the lowest income household quintile (HG1) has access to 54% of the funds and the amount is progressively reduced with the highest income household quintile only having access to 2% of the funds. In summary, the scenarios we explore are:

1. **ECO (with economic rent)** – Efficiency improvements are supported through ECO but we assume that there is a large economic rent present. We treat the rent as money lost and not recycled back into the economy.
2. **ECO (without rent)** – Efficiency improvements are supported through ECO but in this case we assume there is no economic rent. In this case the amount directly used for efficiency improvements almost doubles.
3. **Loans to beneficiaries** – Here we assume that efficiency improvements are supported via interest-free loans issued to the households retrofitting their properties. The repayment period is 10 years and starts in the year that each household receives the retrofitting, meaning that the last repayments end in year 25, 9 years after the end of the retrofitting programme. We assume that loan repayments precede any consumption need so they effectively reduce disposable income.
4. **Fully socialising the cost through income tax** – In this case the government issues grants to fund efficiency improvements. The funds for the grants are raised by adjusting an endogenous income tax to achieve a balanced government budget. The implication is that once the government achieves budget savings, they are recycled back to the economy through the income tax. The grants are issued for a specific purpose so they do not cause any income effects to the recipient households.

Table 1 summarises the cost of each scenario, how the funds are distributed to different sectors and what are the efficiency gains under the different distribution approaches.

⁷ Please note that while we capture spending on imported boilers by UK consumers, our UK model does not incorporate overseas production.

Table 1
Summary of data used to inform scenarios.

	ECO (with economic rent)	ECO (no rent present)	Loans to beneficiaries	Fully socialising through income tax
Amount Spend on Constructions (% of total)	3567.84 (33%)	6957.29 (64%)	8569.84 (87%)	8569.84 (87%)
Amount Spend on Boiler manufacturers (% of total)	644.06 (6%)	1255.91 (12%)	1255.91 (13%)	1255.91 (13%)
Economic rent (% of total)	4001.30 (37%)	0 (0%)	0 (0%)	0 (0%)
Search costs (% of total)	1612.54 (14%)	1612.54 (14%)	0 (0%)	0 (0%)
Administrative costs (% of total)	1071.28 (10%)	1071.28 (10%)	0 (0%)	0 (0%)
Total cost paid by consumers (£million)	10,897.03	10,897.03	9825.75	9825.75
Total efficiency gains when access distributed equally (in %)	HG1-5 (per household quintile)	2.38%	4.64%	5.66%
Total efficiency gains with tapered distribution (in %)	HG1	4.37%	8.53%	10.14%
	HG2	2.44%	4.76%	5.79%
	HG3	1.91%	3.73%	4.61%
	HG4	1.85%	3.62%	4.47%
	HG5	1.33%	2.59%	3.29%

3.2. The UKENVI CGE model

We now turn our attention to explaining the CGE approach we use to simulate each of these scenarios. In the interests of brevity, here we focus on the key specification of the model driving the outcomes reported in Section 4. A full presentation of the model is included in Appendix A.

3.2.1. Model and scenario data

Here we use the dynamic UKENVI computable general equilibrium, CGE, multi-sector model of the UK economy. UKENVI in our work is calibrated on a 2010 social accounting matrix (SAM)⁸ that incorporates an estimated industry-by-industry input-output (IO) table of the UK. The data on the funding available through ECO are taken from the 2019 edition of BEIS Household Energy Efficiency Statistics (HEES). The information available in this publication detail the ECO spending up until 2018 (year 6 in our simulations) so for the period 2019–2028 we assume fixed funding availability each year, equal to the amount available in 2018. Through HEES we also obtain information on the number of households that received efficiency improvements. This way we can determine the amount allocated per beneficiary household and through that the number of beneficiary households in the period 2019–2028. Based on the number of beneficiary households we can also identify what share of each household quintile is receiving efficiency improvements.

For the efficiency improvement of each more efficient household we use data from the National Energy Efficiency Data (NEED) framework. NEED reports the mean energy savings for a range of implemented retrofitting activities. Using historical data on the efficiency gains (reductions in energy use to deliver a given level of consumption activity) achieved by retrofitting activities means that we do not have to rely on arbitrarily imposed assumptions about efficiency improvements per retrofitted property as is often the case in CGE studies. We use the gains reported for ‘Condensing Boiler and Cavity Wall Insulation and Loft Insulation’ as an indication of the efficiency achieved per more efficient household. The data cover the period 2013–2016 so for the 2017–2028 period we assume that the efficiency gains are the average of the 2013–2016 period. Although there is some variation in the efficiency gains of each beneficiary household in the period 2013–2016, which is reflected on our analyses, the average efficiency gains per beneficiary household across the 2013–2028 period is 17.2%. We use this figure and the share of households in each quintile that receive an improvement to determine the efficiency improvement of the whole quintile. For example, if in 2019 75,750 households in HG1 receive efficiency

improvements this is 1.39% of HG1. With each beneficiary household being 17.2% more efficient, this means that the whole quintile is on average 0.24% (17.2 % × 1.39 %) more efficient. Adding together the efficiency gains of each year gives us the total efficiency gains of the entire programme (see Table 1).

3.2.2. Sectors included in our model

UKENVI incorporates all sectors of the UK economy. This allows analysis to capture interactions between the different sectors and markets and identify how changes in one sector can spill across the entire UK economy through changes in prices and incomes generated in different markets and the availability of constrained supplies of labour and capital. We aggregate the 103 sectors reported in ONS IO accounts to 30 sectors. This includes five energy supply sectors: coal extraction, crude oil extraction, refined petroleum, electricity and gas distribution sectors. The aggregation (or not) of the other 25 sectors permits key activities impacting or impacted by the response to enabling and realising energy efficiency to be distinguished. Here we use a similar aggregation to Figus et al. (2017), with the differences being the disaggregation of ‘Manufacture of fabricated metal products, excluding weapons & ammunition’ sector, which is the provider of gas boilers, from the aggregated ‘Iron, Steel and Metal’ sector and the further aggregation of ‘Recreational’ and ‘Other Private Services’ sectors. See Table B.1 for a complete list of sectors modelled.

3.2.3. Modelling production activity

In UKENVI we use a nested KLEM production function where capital (K), labour (L), energy (E) and non-energy (materials, M) intermediates are combined to produce the output of each sector. A key difference to other CGE models is that we distinguish between energy and non-energy intermediates. Capital and labour are combined in one nest of a CES consumption function to produce value added before combining with intermediates, energy and non-energy, dependent on relative prices. Here, we assume a fixed nominal wage. This is to reflect the fact that there have been limited changes in UK wages in the period since the first implementation of ECO. Crucially though, a fixed nominal wage assumption allows us to capture the price pressures driven by the retrofitting activity and the additional household consumption, without them being influenced by variations in the labour cost.⁹

We also assume a fixed (national) labour supply, a common

⁸ The SAM is publicly available at: <https://doi.org/10.15129/7b6e088f-c9ef-4ec4-9df7-58c46ec23d67>.

⁹ Our assumption of a fixed nominal wage may be contentious for some readers in the context of a fixed labour supply. Wage pressures due to the fixed labour supply that would limit the potential expansion of the economy, do not manifest due to the assumption of a fixed nominal wage. We acknowledge those potential concerns and therefore we are relaxing the fixed nominal wage assumption in our current research on residential energy efficiency in the UK.

assumption for national CGE models, meaning there is no migration of additional labour from outside of the UK to meet the excess labour demand. The base year data incorporate a small (6%) pool of unemployed labour that responds to additional employment opportunities and through which the labour demand is covered. We assume perfect mobility of employees to other sectors where increased demand for their output also leads to increased labour demand. Capital is also constrained in that it does not immediately reach the desired level. Instead, we assume that the UK producers are forward-looking with perfect foresight (i.e. they fully anticipate all future price changes, demand levels and capital requirements in each subsequent year). Thus, they gradually adjust productive capacity through investment activity in each year until the desired level of capital stock in each sector is achieved in the long-run. The path of the investment is calculated so that it maximises the value of the firms, while taking into account the depreciation of existing capital (see Appendix A).

3.2.4. Modelling consumption

UKENVI includes a number of consumers including the government and households. In our model, the government consumption is treated as exogenous meaning that despite any changes in relative prices the government is assumed to maintain the same level of consumption. This affects the budget balance, but in most simulations the government can accumulate savings or deficit. The only scenario where we assume a balanced budget is when we simulate the full socialisation of the cost of efficiency improvements through the income tax. In that case the government still maintains the same level of consumption but adjusts the income tax either up or down to achieve a balanced budget.

The UK household sector is disaggregated into 5 quintiles/representative household groups based on gross nominal incomes. This allows us to study how households with varying income levels differ in their consumption of goods and services, including energy goods and services. We assume that households are myopic, meaning that they make consumption decisions based on the income available each year on the basis that this is more representative of the way that particularly low income households (a particular focus in our analyses) decide on how to spend their income.¹⁰ Household income comes from different sources, including labour income, income from capital and transfers from the government. Each quintile has a different marginal propensity to consume, which is assumed to be constant throughout the duration of our analyses. The initial consumption choices of each quintile are informed by the SAM data used as the basis for this model. However, the households respond to changes in the relative price of goods and services, so that they can maximise their utility; subject to budget constraints that fluctuate with every simulated period. This includes the consumption of residential energy, i.e. the energy required for households to run their properties, and an efficiency parameter on energy use that is shocked in our scenarios. As such, our analyses capture any indirect feedback effects driven by a drop in the relative price of residential energy, or by a general increase in the disposable income of households, which enables increased consumption demand for all goods and services.

3.2.5. Trade

UKENVI includes two external regions; Rest of EU (REU) and Rest of the World (ROW). Goods and services from these external regions can be imported for intermediate or final use and similarly UK industries have the option to export their output to these regions. We assume that the prices of non-UK produced goods remain fixed and that UK and external goods and services are imperfect substitutes. Import and export demands respond to changes in relative prices. In each simulated period firms can

choose to either use domestically produced intermediate inputs or import them from abroad. However, since they are considered as imperfect substitutes, a greater difference in relative prices is required for the UK firms to opt to use imports rather than use domestic goods and services. A similar process applies to consumers, who have the option to meet their needs by using domestic or imported goods and services. The base elasticity we assume between domestic and imported goods is in line with the existing literature and is generally accepted as being a reasonable assumption (Turner, 2009).

4. Results and discussion

Through the analysis of the scenarios presented above we seek to achieve three main objectives. First, to identify the impacts of the retrofitting activity and how these are influenced by the mechanism used to fund relevant projects. Second, to study how the funding mechanism affects the extent of efficiency gains and, thus, the long-term impact of efficiency improvement projects. Third, to explore how the results vary if access to funding is distributed in different ways.

4.1. Enabling stages: the potential impacts of retrofitting

The enabling stage of an energy efficiency improvement programme is the period in which funding is available to support the retrofitting of existing properties and thus is the period in which all of the retrofitting activity is observed (Turner et al., 2020). The potential economy-wide impacts of enabling energy efficiency projects depend on the amount of funds directed to retrofitting activities, which links to the funding mechanism used. Such activity is transitory, with any gains limited mainly to the duration of this enabling stage. When UK residential energy efficiency improvements are funded through ECO, in programmes running between 2013 and 2028, we observe potential GDP gains between 0.02% and 0.04% during this timeframe (see Fig. 1). The outcome depends on the presence or not of economic rent, which can limit the funds directed to retrofitting, ranging from £8,213m down to a minimum of £4,212m. The maximum job creation associated with the resulting economic expansion ranges between 6,500 and 11,450 full-time equivalent (FTE) jobs depending on the presence of rent. In all cases, assuming no other changes, the expansionary impacts on the economy virtually disappear the year after the end of the programme.

A key difference between ECO and the alternatives considered here is that cost recovery through energy bills causes households to act, where possible, to adjust their spending to account for this price increase. Under the alternative funding options we explore – involving loan repayments or increased income taxation – the disposable income of households, and thus spending on a range of goods and services, is directly reduced. Therefore, under both alternatives, this enabling stage leads to GDP and employment losses for most years (Fig. 1). When loans

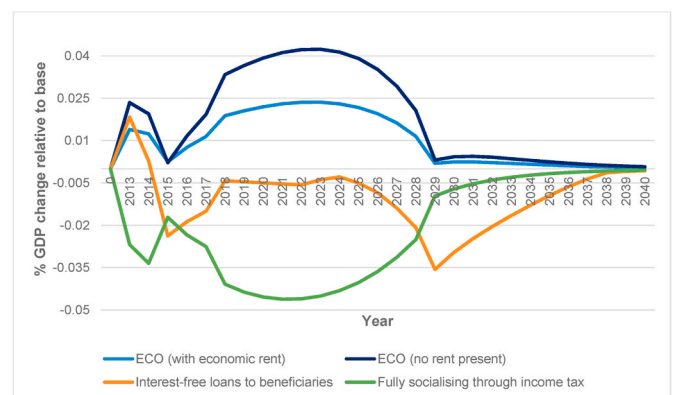


Fig. 1. Comparison of GDP changes under different funding options (central case, enabling stage only).

¹⁰ The alternative would be to assume that households are forward-looking and that they make their consumption decisions based on the future discounted utility of consumption (Lecca et al., 2014).

fund efficiency improvements, we observe a temporary 2-year period of economy-wide gains at the beginning of the programme but, as repayments exceed the duration of the programme, the recovery to the original, pre-retrofitting, GDP levels takes 10 years longer compared to when we fully socialise the cost via income tax.

One useful interpretation of the enabling stage results is that they demonstrate the potential wider economy impacts if, for whatever reason, no efficiency gains actually materialise from retrofitting. Despite some fluctuation, due to different annual funding availability, ECO always delivers economy-wide gains regardless of whether the expected efficiency gains are achieved. Furthermore, with ECO, the disposable income of the lowest income households (HG1) always receives a boost. Income quintiles HG2-4, depending on the presence or not of rent, may experience some temporary income losses but they are less than £2 per household per year and for a maximum period of 2 years.

In contrast, the loan finance and full socialisation options will generate net losses for an extended period of time, unless the expected efficiency gains are realised and compensate for net costs incurred in the enabling stage. Moreover, the additional burden placed on the households to repay the cost of retrofitting may lead to significant and longer-term disposable income losses. Greater potential for income losses is observed when loans are used to cover the cost, leading to potential income losses for a 24-year period, ranging from up to £21 per household per year for HG1 households to up to £35 per household per year for HG5 households. A key observation is that when cost is covered via loans, there is a relatively small difference in the income losses between the different quintiles, which is not the case when the cost is fully socialised. If we use income tax to cover the cost, income losses are increasing in a progressive way as we move towards more affluent households.

4.2. Considering the entire programme: enabling and realising stages

To ensure sustained net economic gains, energy efficiency gains must be realised. The period of an energy efficiency improvement policy in which efficiency gains are achieved constitutes the realising stage of the policy. The extent of efficiency gains achievable depends on the amount of funding actually directed to enabling efficiency improvements. When ECO funds retrofitting projects, in the presence of rent, data suggest that each household quintile (on average/in aggregate) uses 2.38% less energy to deliver the same consumption, interpreted here as becoming 2.38% more energy efficient (see Table 1).¹¹ In the absence of rent, this can rise to 4.64%. Under the loan funding or socialising mechanisms, each quintile could realise efficiency gains of 5.66%. The difference in efficiency gains underpins a divergence in the extent and time path of long-term economic gains realised, shown for GDP in Fig. 2.

Table 2 provides a summary of how a number of key macroeconomic variables can be impacted if we achieve the maximum efficiency gains possible for each of the funding mechanisms. We can see that ECO (with rent) can ultimately deliver a sustained GDP boost of 0.07% per annum and just over 19,500 new FTE jobs. In the absence of rent, these gains grow to 0.14% and 37,400 FTE jobs. This expansion is driven by more energy efficient households having and reallocating more real disposable income to spend on other goods and services. With more funds directed to retrofitting under the alternatives, greater sustained gains can be realised. Under the loan approach, the sustained expansion is reflected in larger GDP and employment gains of 0.17% and over 45,200 FTE jobs. However, socialising the cost through income tax enables the best economy-wide results, delivering a sustained GDP expansion of 0.25% per annum and over 64,700 new FTE jobs. Funding energy efficiency through income tax enables a £64 per household per year income boost for the lowest income (HG1) households, £8 more than is achieved

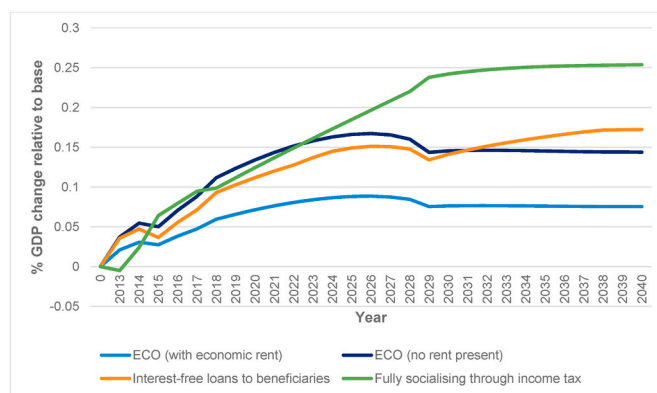


Fig. 2. Comparison of GDP impacts under different funding options (central case, combined enabling and realising stages).

under the private loans approach. The gap widens in higher incomes households, up to £123 (per household per year) in HG5.

One key point to note here is that, while the income tax and loan approaches enable the same efficiency gains, the divergence in economy-wide and income boost results is a function of the income tax process modelled here (detailed in Section 3.2), which recycles public budget gains back to households over time. This is done via income tax reductions generating an additional household income and spending stimulus over time. Overall, our findings highlight that energy efficiency improvements as currently funded by ECO or by alternatives, can deliver wider economy and societal gains. For example, energy efficiency improvement programmes can ultimately deliver between 1.8 and 6.6 FTE jobs, and between £4.3m and £14.1m cumulative GDP gains, per £m spent (Table 2).

However, *net* wider economy gains will be underpinned by differential rates of expansion, depending on where households reallocate and devote increased real spending. Moreover, the expansion observed here is effectively demand driven, triggered by impacts on real household incomes and consumption spending. This puts upward pressure on factor and consumer prices. The outcome is competitiveness effects that partly or wholly offset potential gains in some sectors. This is reflected in the CPI increase and export losses we observe for the majority of the examined programmes duration (see Table 2). Ultimately, in the scenarios modelled here, this is not sufficient to generate net losses in any UK industry identified outside of the energy supply industries (where demand falls with efficiency). The key sectoral level outcome is a shifting composition of UK GDP with domestic spending crowding out export demand, as illustrated for employment in Fig. 3.

4.3. The impacts of changing the distribution of funding

The scenario simulation approach adopted here is also useful to consider how changes in programme delivery may effect outcomes. One UK policy concern is whether less affluent households should receive greater access to ECO funding. Ofgem states one of ECO's goals is to tackle fuel poverty.¹² To meet this goal, policymakers may consider a tapered distribution, providing greater access to funding to the lowest income households. This is not current practice in the ECO framework that we consider first here as a potential benchmark, not least given its fuel poverty objectives. In our experiment, the approach does not affect the total amount spent under each funding mechanism, but it does affect the efficiency gains in each of the household quintiles.

We consider a case where the lowest 20% of households receive 54% of the ECO funds available. Where the large rent is present, data suggest

¹¹ Section 3.2 offers a detailed explanation on the calculation of efficiency gains.

¹² As is mentioned in ECO section of the Ofgem website: <https://www.ofgem.gov.uk/environmental-programmes/eco>.

Table 2
Impact on key macroeconomic variables due to ECO, loans and fully socialising the cost of energy efficiency (central case).

	Base values	ECO (with economic rent)		ECO (no rent present)		Loans to beneficiaries		Fully socialising through income tax	
		First year	Full adjustment	First year	Full adjustment	First year	Full adjustment	First year	Full adjustment
GDP	£1,305,907m	0.02%	0.07%	0.04%	0.14%	0.04%	0.17%	-0.01%	0.25%
CPI	1	0.06%	0.00%	0.08%	0.00%	0.04%	0.00%	-0.02%	0.00%
Investment	15%	0.04%	0.08%	0.06%	0.15%	-0.03%	0.18%	0.18%	0.27%
Unemployment rate	6%	-0.60%	-1.23%	-1.06%	-2.35%	-1.03%	-2.84%	0.14%	-4.07%
Employment	24,930,573	9573	19,567 FTE	16,894	37,410 FTE	16,338	45,240 FTE	-2171	64,741 FTE
Real wage	1	0.06%	0.00%	0.08%	0.00%	0.04%	0.00%	-0.02%	0.00%
Imports	£452,832m	0.07%	0.08%	0.14%	0.15%	0.13%	0.18%	-0.02%	0.27%
Exports	£452,832m	-0.05%	0.00%	-0.08%	0.00%	-0.07%	0.00%	0.02%	0.00%
Total energy use	£190,271m	-0.09%	-0.22%	-0.10%	-0.42%	-0.04%	-0.51%	-0.07%	-0.43%
Disposable income (excluding savings)	£1,427,453m	0.01%	0.14%	0.03%	0.28%	0.06%	0.33%	0.03%	0.39%
Household total energy consumption	£38,856m	-0.36%	-0.56%	-0.40%	-1.08%	-0.13%	-1.31%	-0.27%	-1.17%
Residential energy consumption	£32,019m	-0.13%	-0.27%	-0.15%	-0.53%	-0.05%	-0.64%	-0.11%	-0.54%
Cumulative GDP per £million spent	0	£0.03m	£4.31m	£0.04m	£8.20m	£0.05m	£9.83m	-£0.01m	£14.10
Employment per £million spent	0	0.88 FTE	1.80 FTE	1.55 FTE	3.43 FTE	1.66 FTE	4.60 FTE	-0.22 FTE	6.59 FTE

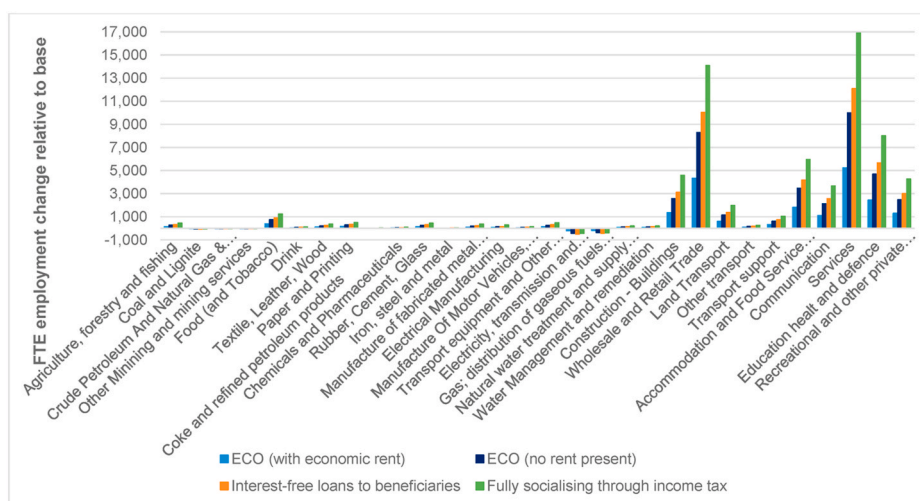


Fig. 3. Long-run employment changes due to different funding mechanisms by UK sector (central case).

that each HG1 household becomes 4.37% more energy efficient. If there is no rent, this can rise to 8.53%. Under loan finance or socialising as alternatives to ECO, more funds would be directed to retrofitting so that HG1 could realise efficiency gains of 10.14%. The range for HG5 households is 1.33% and 3.29% (see Table 1).

The greater efficiency gains observed at the lowest and second lowest income quintiles (HG1 and HG2) lead to greater income gains for these households, while there are smaller gains in the remaining quintiles. See Fig. 4. There is a significant gap in the real income outcome for HG 1 between the tapered and equal distribution. This gap can be up to £30 per household per year, when we fully socialise the cost, as HG1 households may ultimately receive a sustained income boost of £94.5 per household per year.

On the other hand, more affluent households enjoy smaller income gains (both proportionate and in absolute terms) if tapered distribution is applied. Despite the differences in the share of the additional income that each quintile consumes, the erosion of income gains spent by the more affluent households is greater than the additional income spent by HG1. Therefore, the resulting boost to consumption demand is smaller. This, in turn, limits the economic expansion driven by energy efficiency

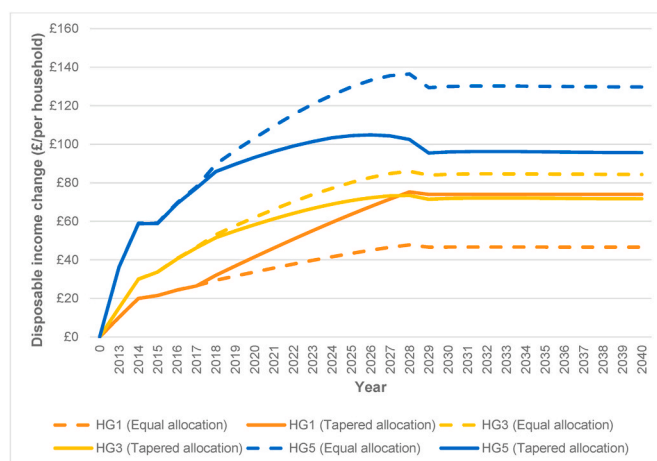


Fig. 4. Comparison of HG1, 3 & 5 disposable income gains under different funding allocation approaches (ECO).

improvement, for example, with the outcome of the fully socialised cost scenario showing a potential sustained GDP boost is 0.23%, compared to the 0.25% that may be achieved using equal distribution (Table 2 above). At a sectoral level, this manifests mainly in smaller sustained gains observed particularly in the consumer spending dominated 'Wholesale and Retail Trade' industry relative to those reported in Fig. 3.

On the other hand, findings regarding household incomes for the enabling stage alone (i.e. if efficiency gains do not materialise) are generally not sensitive to the distribution of funds, with one exception, loan funding. Here low income households have to cover the majority of the loans. Thus, in the absence of energy efficiency gains, paying for projects will result in disposable income losses (up to £58 per household per year) exceeding those suffered in other income quintiles.

5. Conclusions and policy implications

Our work demonstrates that both enabling residential energy efficiency gains and realising the outcomes through an existing energy efficiency programme, such as ECO, in the UK translates to real potential to deliver wider economy benefits. However, the underlying driver of sustained gains is actually realising energy efficiency gains, and how this impacts the disposable income and spending power of households. Thus, our results for scenarios comparing different distributions of project funds show that there may be a trade-off in terms of tailoring energy efficiency programmes to mitigate social issues such as fuel poverty, where gains from focussing on making lower income households more energy efficient unlock a lower extent of expansionary power than those resulting from more broadly distributed gains.

On the other hand, long term programmes to enable efficiency gains, such as UK ECO, can deliver some extent of economy-wide benefits and boost the incomes of the lowest income households, regardless of whether the potential efficiency gains materialise or not. However, as with any investment activity, the economy-wide and household income gains from the retrofitting (enabling) stage are limited, both in terms of timeframes where benefits transpire and relative to returns driven by the efficiency gains. As households become more efficient, their energy bills reduce, thereby freeing up and boosting real purchasing power in favour of other goods and services. Our analysis shows that the administrative and costs associated with identifying appropriate projects (search costs) erode the benefits achievable if the same amount were to be used directly for efficiency improvement activities. Furthermore, the presence or not of economic rent is a key determinant of the magnitude of potential economy-wide and household income gains through ECO. We find that funding through loans or taxation enable more funds to be directed to actually enabling efficiency gains, and, thus, the potential to deliver better economy-wide and household income returns than ECO, but only if those efficiency gains transpire. If not, there is the potential for transitory but significant economy-wide and household income losses in some timeframes.

The broader policy-relevant insight coming from our work is that there are trade-offs that need to be considered when designing energy efficiency policies. The results presented here clearly demonstrate that it may not be possible to combine funding mechanisms and distribution of funds in a way that maximises potential gains across all policy objectives. In the UK case studied here, we found that it was not possible to

Appendix A. Methodology

The UKENVI CGE model

For this paper, we use a dynamic economy-wide multi-sector CGE model of the UK, UKENVI. The model includes all the sectors of the UK economy aggregated to 30 groups and captures the links between the sectors and the effects that relative price changes may have across the entire economy. The model we use here is based on the model used in previous work focussing on household energy efficiency in the UK (Lecca et al., 2014) and incorporates elements like the disaggregation of households into income quintiles, included in more recent research work (Figus et al., 2017). For the

achieve simultaneously the best economy-wide impacts and the best income boost for the lowest income households, while ensuring that there will not be any negative impacts under any circumstances. Therefore, one key message from our work relates to the importance of defining objectives and prioritising the goals of energy efficiency policies, before selecting the combination of funding mechanisms and access distribution that can deliver for those specific goals.

Despite the important policy insights derived by our economy-wide analysis, going forward it will be necessary to update the CGE model database (currently relying on a 2010 analytical input-output table converted from published UK supply-use data) to provide more policy-facing insights. Crucially, the passage of time and changes in economic conditions mean that changes in the structure of the UK economy are likely to have occurred, and that these may affect the magnitude, if not the qualitative nature, of the impacts identified. In this regard, we reiterate the need for caution in assessing the outcomes of the CGE analyses, which should never be taken any form of forecast of the evolution of the wider UK economy.

Data statement

The model used in this study is calibrated using a 2010 Scottish Social Accounting Matrix (SAM) with households disaggregated by gross income. The SAM is publicly available at via the following link: <https://doi.org/10.15129/7b6e088f-c9ef-4ec4-9df7-58c46ec23d67>.

Funding

The authors acknowledge support from the UK Engineering and Physical Sciences Research Council (EPSRC) under Grant [EPSRC ref. EP/M00760X/1] and linked institutional (University of Strathclyde) distribution of EPSRC Impact Accelerator funding.

CRediT authorship contribution statement

Antonios Katris: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Funding acquisition. **Karen Turner:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Project administration.

Declaration of competing interest

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

Acknowledgements

The authors would like to thank Michael Twist, Calum Knox, James Wall, Chris Nicholls and Jack Butland of Clean Growth team at the UK Department for Business, Energy and Industrial Strategy (BEIS) for their contribution to the research reported here. Their comments and feedback on the analysis, and assistance in accessing to the necessary data, has been instrumental to the completion of this work. We are also grateful to Kusum Vishwakarma for invaluable research assistance.

purposes of our work we assume that the labour supply is fixed, a common assumption for national CGE models, while we also assume fixed nominal wage. The latter assumption was used to reflect the relatively small changes in wages in the UK since 2013, the time that ECO was first introduced.

Production

Our model uses a nested constant elasticity of substitution (CES) production function. The sectors are producing output by combining value added and intermediate inputs. In turn, value added is the combination of capital (K) and labour (L), while intermediate inputs are distinguished between energy (E) and non-energy (materials, M) intermediates. Intermediates can be either domestically produced or imported but we assume they are imperfect substitutes under an Armington assumption (Armington, 1969).

Investment

In this work, we assume forward-looking producers with perfect foresight. The desired long-run level of capital stock is known, as are all future prices, capital requirements and demand levels, and are factored into the investment decisions of UK production sectors. Their investment decisions follow Hayashi (1982) with the optimal path of investment derived from maximising the V_t value of firms subject to a capital accumulation function K_t^* :

$$\text{Max} V_t \sum_{t=0}^{\infty} \left(\frac{1}{1+r} \right)^t [\pi_t - I_t(1+g(x_t))] \quad [1]$$

Subject to $K_t^* = I_t - \delta K_t$. In equation [1] π_t is the firm's profit, I_t is the private investment, r is an endogenously determined discount factor and $g(x_t)$ is the adjustment cost function, where $x_t = I_t/K_t^*$, and δ is depreciation rate. The solution of this intertemporal problem allows us to calculate the shadow price of capital in each time period, which changes year by year until a new equilibrium is achieved, and the time path of investment which is related to the tax-adjusted Tobin's q . Essentially, the capital stock in our model does not instantaneously adjust to the desired levels, instead the producers make continuous investments over time until the long-run capital stock level is achieved.

Consumption

We identify a number of consumers in our model but the most relevant for this work are households and the government. Regarding households, they are disaggregated into 5 quintiles based on their gross annual income. We assume that households are myopic, making their consumption decisions based on their current income rather than future discounted utility of consumption (Lecca et al., 2014). Each household quintile in our model makes consumption decisions in each time period based on the following general form:

$$C_{h,t} = Y_{h,t} - S_{h,t} - HTAX_{h,t} - CTAX_{h,t} \quad [2]$$

where C represents the total consumption, Y is the income, S are the savings, $HTAX$ is the income tax and $CTAX$ is the direct tax on consumption; all for period t .

Government

The government in our model is operating according to the following budget constraints where the government budget (GB) is derived by the government revenue (GY) minus the government expenditure ($GEXP$):

$$GB_t = GY_t - GEXP_t \quad [3]$$

$$GY_t = d^s \sum_i r k_{i,t} \cdot K_{i,t} + \sum_i IBT_{i,t} + \bar{\tau}_t \sum_i L_{i,t} \cdot w_t + \overline{FE} \cdot \varepsilon_t \quad [4]$$

$$GEXP_t = \sum_i \bar{G}_{i,t} \cdot P g_t + \sum_{dngins} \overline{TRG}_{dngins,t} \cdot P c_t + \sum_h Grants_{h,t} \quad [5]$$

In the previous equations we can see that GY is the sum of share d^s of capital revenue transferred to the government, IBT is the indirect business tax, L is revenue from labour income at rate τ and FE are the payments/transfers from abroad converted using fixed exchange rate ε . On the other hand, $GEXP$ includes spending on goods and services G and transfers TRG to non-governmental domestic institutions $dngins$, which are assumed to be fixed, and the amount offered as grants to households (but this is only applicable in one of the scenarios we examine). For the purposes of our work, $GEXP$ in general is assumed to be fixed so the government spends the same amount on goods and services over the different periods, only adjusting where the spending is directed following changes in relative prices. This assumption also implies that when a balanced budget is necessary this needs to be achieved through increases in the revenue GY .

Modelling how the cost is covered

ECO

A key difference of ECO, compared to the other funding approaches we examine, is that the cost is passed to the entire consumer base of energy companies via their energy bills. Only the residential consumers cover the cost of ECO, so to capture the necessary increase in energy bills we have re-specified the energy price paid by households:

$$P_{ene} = P_{enemc} \times (1 + \theta) \quad [6]$$

P_{enemc} is the price of energy in a perfectly competitive market, θ is a mark-up and P_{ene} is the price paid by households. The difference between the price paid by households and the competitive market price is the marginal profit of the energy companies.

$$mp = P_{ene} - P_{enemc} \quad [7]$$

If the marginal profit is then multiplied to the total revenue of the energy companies, the product needs to be equal to ECO.

$$\overline{ECO} = mp(P_{ene} \cdot Q_{ene}) \quad [8]$$

With ECO being exogenously determined and having functions for all the other endogenous variables, we can solve equations [6] to [8] for the mark-up required so that energy companies recover the cost of ECO through their residential customers.

Interest-free loans

In terms of how we model the repayment of household loans, we follow a rather simple approach. First, we assume that the loans are repaid over 10 years, starting from the year that retrofitting takes place. Therefore, a household that receives the retrofitting in year 5 will repay the loan by year 15 and as a result the repayment period exceeds the duration of the retrofitting programme. An important point to keep in mind is that loan repayments are assumed to be the top priority of households. This means that first they cover the cost of their instalments and then, with the remaining disposable income, cover the rest of their needs. The result coming from this assumption is that consumption is suppressed compared to what could have been in the absence of the loan repayments.

Government grants

For the government grants, we assume that they can only be used to support energy efficiency improvement projects. Therefore, we have net negative impact on the household income. As we can see in [5], grants increase the government expenditure so for the government to raise the necessary funds, or cover the cost, we use an endogenous income tax process and require a balanced government budget. This way the cost is spread across the economy in a progressive way via the income tax. A key point to highlight regarding this approach is that as the government increases the income tax to cover any budget deficit, in the same way it decreases the income tax to return any budget savings back to the households.

Data

As mentioned in Section 3.2, the model for our study is calibrated using a 2010 UK Social Accounting Matrix (SAM), given that (at the time of conducting the research) this was the most recent year that the required economy-wide input-output data were available in appropriate form for the UK. The 103 sectors reported in ONS IO accounts are aggregated to 30 sectors, including five energy supply sectors: coal extraction, crude oil extraction, refined petroleum, electricity and gas distribution. We also keep 'Manufacture of Fabricated Metal Products, excluding weapons & ammunition' sector at the lowest aggregation level possible (see Table B1).

As detailed above (Section 3.2) our scenarios were informed using publicly available data from the 2019 edition of BEIS Household Energy Efficiency Statistics (HEES) for the cost of the efficiency improvement programmes and from the National Energy Efficiency Data (NEED) framework for the expected efficiency gains. The information on the allocation of access to funds under the tapered approach are the outcome of internal analyses at BEIS and were provided to us by our collaborating colleagues in BEIS.

Appendix B. The sectors in our CGE model

Table B.1

Sectoral aggregation in CGE model and link to SIC2007 codes

Sector Number	Sector Name	SIC code
S1	Agriculture, Forestry and Fishing	01–03
S2	Coal and Lignite	05
S3	Crude Petroleum And Natural Gas & Metal Ores	06–07
S4	Other Mining and Mining Services	08–09
S5	Food and Tobacco	10&12
S6	Drinks	11
S7	Textile, Leather and Wood	13–16
S8	Paper and Printing	17–18
S9	Coke and Refined Petroleum Products	19
S1	Chemicals and Pharmaceuticals	20–21
S11	Rubber, Cement and Glass	22–23
S12	Iron, Steel and Metal	24&25.4
S13	Manufacture of Fabricated Metal Products, excluding weapons & ammunition	25.1–3&25.5–9
S14	Electrical Manufacturing	26–28
S15	Manufacture Of Motor Vehicles, Trailers and Semi-Trailers	29
S16	Transport Equipment and Other Manufacturing (incl. Repair)	30–33
S17	Electricity, Transmission and Distribution	35.1
S18	Gas; Distribution of Gaseous Fuels Through Mains; Steam and Air Conditioning Supply	35.2–3
S19	Natural Water Treatment and Supply Services	36–37
S20	Waste Management and Remediation; Sewerage	38–39
S21	Construction - Buildings	41–43
S22	Wholesale and Retail Trade	45–46
S23	Land Transport	47&49.1–2
S24	Other transport	49.3–5&50
S25	Transport support	51
S26	Accommodation and Food Service Activities	53&55
S27	Communication	52&56-62
S28	Services	63–80
S29	Education, Health and Defence	81–85
S30	Recreational and Other Private Services	86–94

References

- Armington, P.S., 1969. A theory of demand for products distinguished by place of production. *Staff Pap. (Int. Monet. Fund)* 16, 159–178. <https://doi.org/10.2307/3866403>.
- Barrett, J., Owen, A., Taylor, P., 2018. Funding a Low Carbon Energy System: a Fairer Approach? *Energy* 143, 191–201. <https://doi.org/10.1016/j.energy.2017.10.103>.
- Bye, B., Fæhn, T., Rosnes, O., 2018. Residential energy efficiency policies: costs, emissions and rebound effects. *Energy* 143, 191–201. <https://doi.org/10.1016/j.energy.2017.10.103>.
- Dahlhausen, M., Heidarinejad, M., Srebric, J., 2015. Building energy retrofits under capital constraints and greenhouse gas pricing scenarios. *Energy Build.* 107, 407–416. <https://doi.org/10.1016/j.enbuild.2015.08.046>.
- Fæhn, T., Isaksen, E.T., 2016. Diffusion of climate technologies in the presence of commitment problems. *Energy J.* 37, 155–180. <https://doi.org/10.5547/01956574.37.2.tfae>.
- Figus, G., Turner, K., McGregor, P., Katris, A., 2017. Making the case for supporting broad energy efficiency programmes: impacts on household incomes and other economic benefits. *Energy Pol.* 111, 157–165. <https://doi.org/10.1016/j.enpol.2017.09.028>.
- Fowle, M., Greenstone, M., Wolfram, C., 2015. DO ENERGY EFFICIENCY INVESTMENTS DELIVER? EVIDENCE FROM THE WEATHERIZATION ASSISTANCE PROGRAMME (No. 21331). Cambridge, MA.
- Geels, F.W., Schwanen, T., Sorrell, S., Jenkins, K., Sovacool, B.K., 2018. Reducing energy demand through low carbon innovation: a sociotechnical transitions perspective and thirteen research debates. *Energy Res. Soc. Sci.* 40, 23–35. <https://doi.org/10.1016/j.erss.2017.11.003>.
- Gerarden, B.T., Newell, R.G., Stavins, R.N., 2015. Deconstructing the energy-efficiency Gap. *Concept. Framew. Evid.* 105, 183–186.
- Gillingham, K., Palmer, K., 2014. Bridging the energy efficiency gap: policy insights from economic theory and empirical evidence. *Rev. Environ. Econ. Pol.* 8, 18–38. <https://doi.org/10.1093/reep/ret021>.
- Gillingham, K., Rapson, D., Wagner, G., 2016. The rebound effect and energy efficiency policy. *Rev. Environ. Econ. Pol.* 10, 68–88. <https://doi.org/10.1093/reep/rev017>.
- Greening, L.A., Greene, D.L., Di, C., 2000. Energy efficiency and consumption - the rebound effect - a survey, 28, 389–401.
- Hayashi, F., 1982. Tobin's marginal q and average q : a neoclassical interpretation author (s): fumio Hayashi reviewed work (s): published by: the econometric society stable URL. *Society* 50, 213–224. <http://www.jstor.org/stable/1912538>.
- Henly, J., Ruderman, H., Levine, M.D., 1988. Energy saving resulting from the adoption of more efficient appliances: a follow-up. *Energy J.* 9, 163–170.
- International Energy Agency, 2014. Capturing the Multiple Benefits of Energy Efficiency. Capturing the Multiple Benefits of Energy Efficiency. IEA. <https://doi.org/10.1787/9789264220720-en>.
- Kiula, O., Rutherford, T.F., 2013. The cost of reducing CO₂ emissions: integrating abatement technologies into economic modeling. *Ecol. Econ.* 87, 62–71. <https://doi.org/10.1016/j.ecolecon.2012.12.006>.
- Laes, E., Mayeres, I., Renders, N., Valkering, P., Verbeke, S., 2018. How do policies help to increase the uptake of carbon reduction measures in the EU residential sector? Evidence from recent studies. *Renew. Sustain. Energy Rev.* 94, 234–250. <https://doi.org/10.1016/j.rser.2018.05.046>.
- Lecca, P., McGregor, P.G., Swales, J.K., Turner, K., 2014. The added value from a general equilibrium analysis of increased efficiency in household energy use. *Ecol. Econ.* 100, 51–62. <https://doi.org/10.1016/j.ecolecon.2014.01.008>.
- Mata, É., Kalagasidis, A.S., 2015. Cost-effective retrofitting of Swedish residential buildings: effects of energy price developments and discount rates 223–237. <https://doi.org/10.1007/s12053-014-9287-1>.
- Mizobuchi, K., 2008. An empirical study on the rebound effect considering capital costs. *Energy* 33, 2486–2516. <https://doi.org/10.1016/j.eneco.2008.01.001>.
- Moglia, M., Cook, S., McGregor, J., 2017. A review of Agent-Based Modelling of technology diffusion with special reference to residential energy efficiency. *Sustain. Cities Soc.* 31, 173–182. <https://doi.org/10.1016/j.scs.2017.03.006>.
- Molina, M., 2014. The Best Value for America's Energy Dollar: A National Review of the Cost of Utility Energy Efficiency Programs.
- Sathitbun-anan, S., Fungtammasan, B., 2015. An analysis of the cost-effectiveness of energy efficiency measures and factors affecting their implementation: a case study of Thai sugar industry 141–153. <https://doi.org/10.1007/s12053-014-9281-7>.
- Scottish Government, 2018. Energy efficient Scotland: route map. <https://www.gov.scot/publications/energy-efficient-scotland-route-map/>.
- Sorrell, S., 2007. The Rebound Effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency. UKERC report. <https://ukerc.ac.uk/publications/the-rebound-effect-an-assessment-of-the-evidence-for-economy-wide-energy-savings-from-improved-energy-efficiency/>.
- Sorrell, S., Dimitropoulos, J., 2007. The rebound effect: microeconomic definitions, limitations and extensions 5. <https://doi.org/10.1016/j.ecolecon.2007.08.013>.
- Trianni, A., Cagno, E., Farné, S., 2016. Barriers, drivers and decision-making process for industrial energy efficiency: a broad study among manufacturing small and medium-sized enterprises. *Appl. Energy* 162, 1537–1551. <https://doi.org/10.1016/j.apenergy.2015.02.078>.
- Tuominen, P., Reda, F., Dawoud, W., Elshafei, G., 2015. Economic appraisal of energy efficiency in buildings using cost-effectiveness assessment. *Procedia Econ. Financ.* 21, 422–430. [https://doi.org/10.1016/S2212-5671\(15\)00195-1](https://doi.org/10.1016/S2212-5671(15)00195-1).
- Turner, K., 2013. "Rebound" effects from increased energy efficiency: a time to pause and reflect. *Energy J.* 34, 25–42.
- Turner, K., 2009. Negative rebound and disinvestment effects in response to an improvement in energy efficiency in the UK economy. *Energy Econ.* 31, 648–666. <https://doi.org/10.1016/j.eneco.2009.01.008>.
- Turner, K., Katris, A., Race, J., 2020. The need for a Net Zero Principles Framework to support public policy at local, regional and national levels. *Local Econ.* 35 (7), 627–634. <https://doi.org/10.1177/0269094220984742>.
- United Nation Framework Convention on Climate Change [UNFCCC], 2015. Paris Agreement.
- Winkler, H., Spalding-fecher, R., Tyani, L., Winkler, H., Spalding-fecher, R., Tyani, L., Matibe, K., 2010. Cost-benefit Analysis of Energy Efficiency in Urban Low-Cost Housing Cost – Benefit Analysis of Energy Efficiency in Urban Low-Cost Housing 3637. <https://doi.org/10.1080/0376883502200001938>.
- Yushchenko, A., Patel, M.K., 2016. Contributing to a green energy economy? A macroeconomic analysis of an energy efficiency program operated by a Swiss utility. *Appl. Energy* 179, 1304–1320. <https://doi.org/10.1016/j.apenergy.2015.12.028>.