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MAKING THE CASE FOR SUPPORTING BROAD ENERGY EFFICIENCY PROGRAMMES: IMPACTS ON HOUSEHOLD INCOMES AND OTHER ECONOMIC BENEFITS

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Making the case for supporting broad energy efficiency programmes: impacts on household incomes and other economic benefits

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Abstract:

In recent years, an overly narrow focus on rebound effects has limited the extent of researcher and policy attention afforded to the wider multiple benefits of increased energy efficiency. The objective of this paper is to focus policy attention on the sustained added value to the economy that is created as result of improving energy efficiency in the residential sector. Governments around the world are committed to increasing energy efficiency more generally, but often focus public support in low income households where energy poverty is a particular concern. However, governments operate in a context of multiple objectives where energy efficiency is expected to deliver significant reductions in carbon emissions alongside sustainable economic development. We use a UK CGE model to consider the general effects of supporting increases in energy efficiency in residential energy use. Our results demonstrate that the increase in GDP, and economic activity more generally, triggered by increased energy efficiency delivers more in terms of increased household incomes than the efficiency improvement itself. We find that the more wide ranging the boost to energy efficiency, the greater the economic expansion and associated returns are likely to be, and the less the means of financing through public budgets will erode the benefits over time.

Key words: energy efficiency, energy demand, fuel poverty, multiple benefits, general equilibrium

JEL codes: C68; D58; Q43; Q48

1. Introduction

In recent years the literature on the wider economic impacts of energy efficiency improvements has tended to focus on the issue of rebound effects. In particular, rebound studies have mainly focussed on measuring direct and indirect ('re-spending') rebound effects using microeconomic or limited input-output economy-wide models (see for example Chitnis and Sorrell, 2015; Druckman, et al. 2011; Freire-Gonzáles, 2011). Where different household income groups are identified, emphasis has tended to be placed on how rebound effects that are driven by changes in real income following an energy efficiency improvement will be bigger the larger the share of total income that is spent on energy consumption (Chitnis et al., 2014; Murray 2013; Thomas and Azevedo, 2013).

However, certainly in colder climates like that of the UK, where lower income households tend to spend a larger share of their income on energy (Office for National Statistics, 2011, 2012, 2013), there are concerns over energy or fuel poverty (UK DECC, 2015).[1] This both raises a challenge for the rebound-focussed literature, in that direct rebound effects triggered by lower energy costs may in fact be a true representation of required demand (to adequately heat properties), and focuses attention on the nature of socio-economic returns from increased energy efficiency.

The latter point reflects the **'multiple benefits of energy efficiency' argument** proposed by the International Energy Agency (IEA, 2014). In particular the current paper focuses attention on the sustained added value to the economy that is created as result of investing in increased energy efficiency. We consider this in the context of a **general equilibrium argument**. That is, we propose that the increase in GDP and economic activity more generally that is triggered by increased energy efficiency (here in the household sector) delivers more in terms of energy poverty reduction than the efficiency improvement itself.[2] This is through the additional return to household incomes as the economy expands. The larger and more wide-ranging the boost to household energy efficiency, the greater the economic expansion and associated returns are likely to be.

We also consider a **government funding argument**, that public support should be directed at helping those less able to pay for energy efficiency improvements themselves. Specifically, we consider whether economic expansion triggered by more wide ranging support of energy efficiency programmes is likely to provide sufficient payback to justify greater levels of public support. This may also provide the basis for setting energy efficiency programmes in the context of a **national infrastructure argument** linked to improving the quality of a country's domestic building stock.

The remainder of the paper is structured as follows. Section 2 reviews the recent indirect and economy-wide rebound literature that has been the recent setting for considering the impacts of increased efficiency in household energy use. We focus on the extent to which wider economic expansionary and socio-economic arguments have been made. Section 3 then focuses attention on the policy context for identifying the issues outlined above, expanding on the multiple benefits, general equilibrium and public funding/national infrastructure arguments. Section 4 describes the UK CGE model that we use to consider the general effects that may be anticipated if energy efficiency increases in one or more household income groups in an economy. Section 5 details the simulation

[1] In warmer climates, cooling may be a greater concern than heating. However, the expense of running air conditioning systems may deter low income households from investing in systems, so that expenditure on cooling does not manifest in economic statistics in the same way as energy poverty linked to heating.

[2] Note that in this paper we do not attempt to investigate impacts on precise measures of energy or fuel poverty currently adopted in the UK. At this stage, in our general analysis, we focus simply on whether the share of disposable income spent on energy goes up or down.

scenarios that are then implemented in Section 6, where we discuss our results. Finally, Section 7 draws conclusions and considers policy implications.

2. Existing literature on the wider impacts of energy efficiency

In recent years a number of studies have analysed the impact of improved household energy efficiency using microeconomic demand systems, and input-output (IO) techniques. Their main focus has been the estimation of direct and indirect rebound effects (see for example Brännlund, et al. 2007; Chitnis and Sorrell, 2015; Druckman et al., 2011; Freire-Gonzáles, 2011; Lenzen and Dey, 2002; Mizobuchi, 2008).

More broadly, the main objective of this literature is to assess the effectiveness of energy efficiency, specifically in reducing energy use and CO_2 emissions throughout the economy triggered by a reduction in final energy demand. For this reason, they estimate the rebound effect as a measure of the extent to which technically possible energy savings are eroded by economic responses.

Some of these studies have estimated energy rebound effects by considering the impacts of energy efficiency and energy saving behavioural changes across different household income groups (Chitnis et al., 2014; Murray, 2013; Thomas and Azevedo, 2013). In this context, a common finding is that the lowest income groups tend to be associated with higher rebound effects. This is for two reasons. First, lower income groups tend to spend a larger share of their income on energy. Second, the price elasticity of demand for energy goods is generally higher when income is lower, indicating that lower income households are more responsive to changes in energy price (Chitnis et al., 2014). When the price of energy in efficiency units decreases, price elastic groups respond by consuming more energy.

However, a key limitation of the approaches adopted in the aforementioned studies is to rely on models that implicitly or explicitly adopt the assumption of fixed market prices and nominal incomes. Such models are not able to capture the full set of economic responses triggered by an energy efficiency improvement that will occur as the economy adjusts to a new steady state with different spending and production decisions. Thus, they are limited in their capability to identify other potential benefits of energy efficiency (Brännlund et al., 2007; Chitnis and Sorrell, 2015; Lecca et al., 2014).

Duarte et al. (2015), and Lecca et al. (2014) have estimated the impact of improving energy efficiency in household energy use using more flexible computable general equilibrium (CGE) models that incorporate IO data but permit the relaxation of the assumptions inherent in partial equilibrium and IO studies. Specifically, Lecca et al. (2014) takes the case of the UK and explores the value added of moving from a partial to a general equilibrium modelling framework (via an intermediate stage involving IO analysis) in the analysis of energy efficiency improvement. This is done by considering the impact of a 5% increase in household energy efficiency using models with different degrees of complexity calibrated on a common database.

Lecca et al. (2014) initially estimate the direct rebound effect by estimating the elasticity of demand for energy goods and then derive the indirect (re-spending) rebound effects using IO techniques. They find that the indirect component of rebound is typically negative when the direct rebound is less than 100% and the economy is characterised by energy sectors that are relatively energy intensive. In their UK case study, households decrease their demand for energy and reallocate spending towards less energy intensive non-energy goods, thereby reducing both direct energy use and energy embodied in supply chains supporting consumption demand. These net negative indirect effects persist when Lecca et al. (2014) derive the full economy-wide rebound using a CGE model. However, here the fuller economy-wide responses to the energy efficiency improvement are influenced by endogenous market price determination, nominal income and supply responses. This implies, for example, that the initial drop in demand for energy decreases the market price of energy in the short-run, exacerbating the rebound effect by amplifying the decrease in the price of energy services (for any given market price), which may be considered as the effective price of energy. However, it also negatively influences the revenue and capacity decisions of energy producing firms and, over time, their output prices (i.e. countering decreases in both the effective and market price of energy). Moreover, the increase in demand for non-energy goods puts upward pressure on domestic consumption prices, negatively influencing competitiveness of UK industries. Nonetheless, overall the Lecca et al. (2014) results show a net expansion in the UK economy, with an increase in investment, employment and household spending. However, with a fixed national labour supply, depending on how households respond to the change in cost of living given by increased energy efficiency, a sustained increase in wages may give rise to a higher price level and reduced export demand.

The Lecca et al. (2014) contribution helps to clarify the importance of analysing the full general equilibrium impacts of increased household energy efficiency. However, it is limited in only considering one single representative household, thereby not permitting any differentiation among household income groups. However, differences in the composition of both incomes and expenditures are likely to be crucial in influencing the distribution of the effects of economic adjustment across household income groups. Here, heterogeneity of households proves to be very important from a policy perspective.

Duarte et al. (2015) also use a CGE model, this time for Spain to assess a range of energy-saving policies including increasing energy efficiency, but identifying four household income groups. They actually find that lower income household are less responsive to an energy efficiency improvement, and indeed are associated with lower rebound effects.[3] However, the main point is that, although the focus of the work is on potential reduction of CO_2 emissions, Duarte et al.'s (2015) results also show that an energy efficiency improvement delivers an economic stimulus with a broader set of outcomes than reducing energy use.

In general, though, much of the rebound literature neglects the wider range of potential economic benefits associated with increased energy efficiency that have been the focus of policy community contributions such as the IAE (2014) report. In response, this paper aims to add to the energy efficiency and CGE literature in filling this gap by exploring the wider impacts of household energy efficiency improvements in more detail, and to do so with specific focus on identifying different impacts among household income groups. In particular we focus on how support of energy efficiency programmes in the household sector may be justified through 'pay back' delivered by macroeconomic expansion.

3. Broadening focus for a 'multiple objectives' policy context

If we broaden focus from estimating rebound effects of increased energy efficiency more carefully to consider the processes that drive them, we implicitly turn attention to what has become known as the **multiple benefits argument.** While this specific terminology originates with the IEA (2014), arguments and evidence that energy efficiency will enhance economic welfare in a range of ways, including as a result of macroeconomic expansion, have been considered in other studies, notably (in terms of reflecting on the recent dominant focus on rebound effects) in the recent contribution by Gillingham et al. (2016).[4]

[3] This may relate to the issue of cooling vs. heating and that in warmer climates, such as Spain, low income households cannot afford more electricity-intensive systems such as air conditioning.

[4] Chan and Gillingham (2015) also provide an analytical exposition of how rebound effects will have positive economic welfare implications at the microeconomic level.

In the current paper, we build on previous CGE studies of increased household energy efficiency to consider the wider economic impacts that fall under the multiple benefits umbrella. In particular, we focus on a **general equilibrium argument** that economic expansion will potentially deliver more in terms of individual household economic well-being than the initial improvement in energy efficiency. That is, when the economy expands (through increased investment, employment and output) as a result of increased and reallocated real household spending, increased incomes from employment of labour and capital services will further boost household incomes.[5] In an energy poverty context, while the expansionary process will trigger further rebound in household use (as well as in the production sector of the economy), this must be set against increased household incomes (and benefits).

Thus, one implication of this general equilibrium argument is that support of energy efficiency will deliver on more than just the outcome of reducing energy use (and related carbon emissions). Rather, by stimulating economic expansionary processes, it will further boost incomes throughout the economy and potentially deliver a level of pay back that would justify the public support required to allow the efficiency improvement to occur.

However, it may be argued that macroeconomic expansion can be delivered through other policies and that, where energy efficiency policy requires the support of the public purse, focus should be on helping those households who are currently unable to heat[6] their homes sufficiently. While the general equilibrium argument above implies that that the more wide-ranging the energy efficiency improvement, the greater will be the benefit to all households, it is necessary to consider whether restrictions on the government budget may erode the multiple benefits. That is, a **government funding argument** must also be considered. In the UK analysis below, we consider the context of a government that requires to maintain a fixed public sector deficit so that any support for energy efficiency programmes must be of a balanced-budget nature. That is to say that the funding for such programmes must come either from a reallocation of existing public spending or a change in tax revenues, at least in the short-term (until the costs of introducing the efficiency improvement have been recovered).

The key issue, then, is whether the resulting expansion is still large enough to compensate for the impacts of falling government expenditure (in the areas where spending is reduced) or the distortions triggered by increasing tax rates in part(s) of the economy. In turn, this is again likely to depend on how extensive the efficiency improvement is and what type and level of spending activity (the trigger for demand-led expansion) occurs as a result of freed up (and increased) household (real) disposable incomes. If the efficiency improvement is limited to low income households, it must be recognised that these households are (a) a more limited source of spending power, and (b) less sensitive to the wage and capital incomes generated by economic expansion, given their greater dependence upon publicly funded benefits. Stimulating higher income households, on the other hand, may free up much more spending on non-energy goods and services and deliver greater benefits through increased wage and capital incomes.[7]

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[5] As we show in the CGE simulations reported in Section 6, where there is any constraint on the supply-side of the economy (e.g. restricted national labour supply) a demand-led expansion will put upward pressure on prices and potentially damage competitiveness. While this may benefit household incomes through higher wage rates, any loss in competitiveness will limit the extent of economic expansion over time. Where the expansion is triggered by increased energy efficiency this may be mitigated if households reflect the change in their cost of living in wage demands. However, we do not explore this issue at this stage.

[6] Or, in the context of warmer climates, to cool.

[7] Of course, in practice differences in propensities to consume and potential for further improvement in what may already be relatively energy efficient higher income homes (where efficiency in the use of luxury

This latter point may ultimately support a **national infrastructure argument**. If it can be shown that the economic stimulus generated by support of wider-ranging energy efficiency programmes is likely to deliver sufficient pay back to justify the initial levels of funding required, then arguments for strategic investment in energy efficiency can be more solidly made. On this basis, the type of quite generalised analysis we offer below is intended as a first step in impacting policy discussion around focussing attention on the broader value added/benefits of, for example, making buildings more energy efficient.

4. Model and data

We simulate the economy-wide and macroeconomic impacts of improving household energy efficiency using a variant of the UK CGE model UK-ENVI.[8] For the specific application in this paper, we assume that investments are made by profit maximising forward-looking agents while (here five) representative households (distinguished as income quintile groups) are myopic. This intended to capture the notion that consumers do not behave "as if" they are all rational economic men, as is often assumed by economic modellers. In particular, households tend to be rather myopic, in contrast to firms, and base their spending decisions more on current income availability rather than on future discounted utility of consumption.[9] In the following sections we provide a description of the main characteristics of the model.[10]

4.1. Consumption

We model the consumption decision of five representative households *h* as follows:

$$C_{h,t} = SHL_h \cdot \left((1-\bar{\tau}_t)L_t^s\,(1-u_t)w_t\right) + SHK_h \cdot \left(\sum_i rk_{i,t}K_{i,t}\right) + Trf_t - S_{h,t} \tag{1}$$

Household income includes the share of labour (*SHL*) and capital (*SHK*) incomes produced within the economy that goes to households, and transfers from other institutions (*Trf*) such as the UK Government, which are fixed in real terms. In (1) τ_t is the income tax rate[11], L^s, is labour supply, *w*, is nominal wage, *K* is capital supply, *rk* is the capital rental rate and *S* are savings.

appliances may be a greater issue than heating/insulation) would have to be considered in any practical case study.

[8] UK-ENVI is a CGE modelling framework designed for the analysis of economic disturbances to the UK economy. The ENVI version is dedicated to the analysis of energy and environmental policies.

[9] It could be argued that lower income households are more myopic that higher income households. Although this is a reasonable observation, we decide to assume the same behaviour for all households given that a) we focus our attention on lower income households and b) long-run results are identical, regardless of the chosen dynamic.

[10] We provide the full mathematical description of the model in Appendix D. .

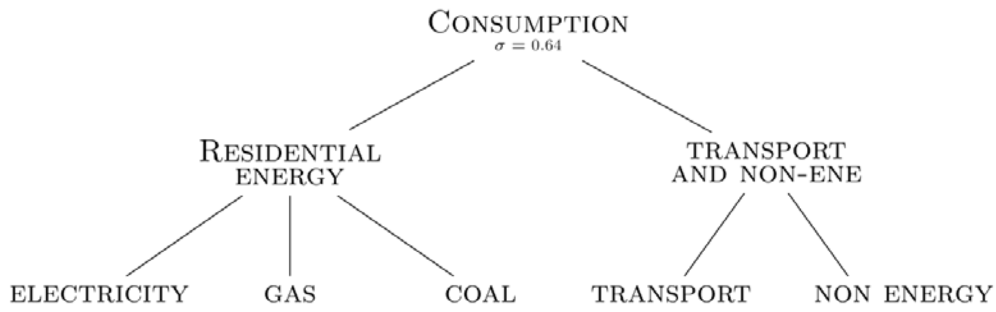
[11] The income tax rate is fixed by default in our model. However, in Sections 5 and 6 we explain how this can be changed endogenously to absorb the cost of energy efficiency enhancing policies.

At each period in time, each household allocates its consumption between energy used for residential purposes, *EC,* and non-energy and transport goods and services (including fuel use in personal transportation), *TNEC,* according to the following constant elasticity of substitution (CES) function:

$$C_{h,t} = \left[\delta_h^E \left(\gamma EC_{h,t}\right)^{\frac{\varepsilon_h - 1}{\varepsilon_h}} + \left(1 - \delta_h^E\right) TNEC_{h,t}{}^{\frac{\varepsilon_h - 1}{\varepsilon_h}}\right]^{-\frac{\varepsilon_h}{\varepsilon_h - 1}} \tag{2}$$

In (2) ε is the elasticity of substitution in consumption, and measures the extent to which consumers substitute residential energy consumption, *EC*, for non-energy and transport consumption, *TNEC,* δ ϵ (0,1) is the share parameter, and γ is the efficiency parameter for residential energy consumption. For simplicity (and in the absence of better information), in all households we impose a value, 0.61, for ε that is the long-run elasticity of substitution between energy and non-energy estimated by Lecca et al. (2014).[12] The consumption of residential energy includes electricity, gas and coal, as shown in Figure 1, although the share of coal consumed by households represents less than 0.01% of total energy consumption. Within the energy bundle, given that we do not focus on inter-fuel substitution in the analysis below, we impose a small but positive elasticity.

Figure 1: The structure of consumption

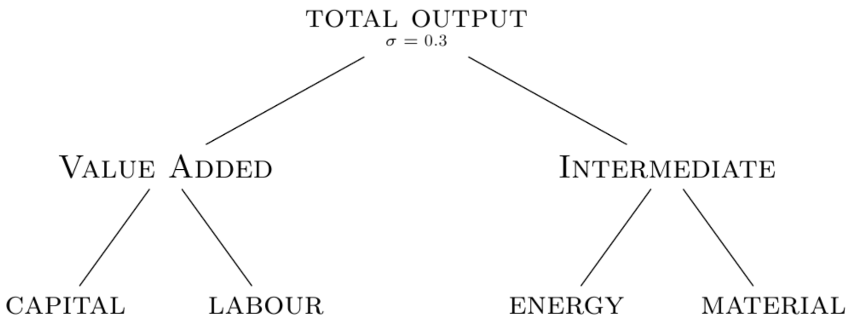


4.2. Production and investment

The production structure is characterised by a capital, labour, energy and materials (KLEM) nested CES function. As we show in Figure 2, the combination of labour and capital forms value added, while energy and materials form intermediate inputs. In turn, the combination of intermediate and value added forms total output in each sector.

[12] However, we have conducted sensitivity analysis where we introduce different values for different household income groups. In particular, we introduced higher values for lower household income groups and vice versa. In comparison to the results reported in Section 4, we find that a higher elasticity triggers a larger rebound effect overall and in the households with higher elasticity. While the impact on overall GDP is not much changed (slightly reduced in the short run), as may be expected, there is a larger boost to disposable income in those groups with a higher elasticity, while the share of income spent on energy falls by less.

Figure 2: The structure of production



Following Hayashi (1982), we derive the optimal time path of investment by maximising the value of firms V_t, subject to a capital accumulation function $\dot{K}_t$, so that:

$$Max\ V_t \sum_{t=0}^{\infty} \left(\frac{1}{1+r}\right)^t \left[\pi_t - I_t\big(1 + g(x_t)\big)\right] subject\ to\ \dot{K}_t = I_t - \delta K_t \tag{3}$$

In (3), π_t, is the firm's profit, I_t, is private investment, $g(x_t)$ is the adjustment cost function with $x_t = I_t/K_t$ and δ is depreciation rate. The solution of the optimisation problem gives us the law of motion of the shadow price of capital, λ_t, and the adjusted Tobin's q time path of investment (Hayashi, 1982).

4.3. The labour market

Wages are determined within the UK in an imperfect competition setting, according to the following wage curve:

$$\ln\left[\frac{wb_t}{cpi_t}\right] = \varphi - \epsilon \ln(u_t)$$

where

(4)

$$wb_t = \frac{w_t}{1 + \bar{\tau}_t}$$

where the real consumption (after tax) wage is negatively related to the rate of unemployment (Blanchflower and Oswald 2009). In (4), $\frac{w_t}{cpi_t}$ is the real take home wage, φ is a parameter calibrated to the steady state, ϵ is the elasticity of wage related to the level of unemployment u_t, and $\bar{\tau}_t$ is the income tax rate. The working population is assumed to be fixed and exogenous.

4.2. Government

The Government collects taxes and spends the revenue on a range of economic activities. We constrain the Government to maintain a constant budget balance. The aggregate fiscal deficit is taken to be fixed, so that any changes are constrained to be balanced budget in nature. The given fiscal deficit is maintained by either adjusting taxation or expenditure as illustrated in Equation (5):

$$\overline{GOVBAL_T} = GY_t - GEXP_T$$

where (5)

$$GY_t = d_g KY_t + IBT_t + \bar{\tau}_t \cdot LY_t + \overline{FE}_t$$

In (5) *GOVBAL* is the government budget which is equal to the difference between government income *GY,* and government spending *GEXP.* GY is given by the share d_g of capital income *KY* that is transferred to the Government, Indirect business taxes, *IBT,* revenues from labour income *LY* at the rate τ[13], and foreign remittance FE. In the base year GOVBAL is negative, indicating a fiscal deficit that we assume to be fixed in our present analysis.

We initially assume that the Government absorbs the budgetary impacts of any change in the economy by adjusting expenditure and keeping household income tax rates fixed. However, as explained below, we explore other cases, including where the Government fixes its expenditure and adjusts the income tax rate.

4.3. Dataset: income disaggregation and energy use

We calibrate the UK-ENVI CGE model on the UK Social Accounting Matrix for 2010.[14] The data has 30 different productive sectors[15] including 4 main energy supply industries that encompass the supply of coal, refined oil, gas and electricity. We identify UK households, the UK Government, imports, exports and transfers to and from the rest of the World (ROW).

Table 1. Quintiles disaggregation in the 2010 UK SAM by weekly income

HG1	HG2	HG3	HG4	HG5
Up to £237	£238 - £412	£413 - £650	£651 - £1,014	£1,015 and over

As noted above (and explained in Appendix B), we disaggregate the household sector into 5 household income quintiles (HG), using the UK Living Costs and Food Survey. The income bands are described and related to weekly gross incomes in Table 1.

Table 2 shows residential energy spending (on electricity, gas and coal) for each household as percentage of total energy consumption and of total consumption spending.

Table 2. Percentage of energy used for domestic purposes in total energy consumption and in total consumption

	HG1	HG2	HG5	HG4	HG5
Res. energy/ Tot. energy	89.6%	85.2%	81.4%	76.2%	69.9%
Res. energy/ Tot. consumption	6.7%	5.5%	4.5%	3.8%	2.6%

[13] Note that this is the same rate reported in Equations (1) and (4).
[14] The SAM is produced by the Fraser of Allander Institute and available for download at: http://www.strath.ac.uk/business/economics/fraserofallanderinstitute/research/economicmodelling/
[15] See Appendix A, Table A.1 for the full list of sectors and the corresponding sectors in the 2010 UK IO table.

As would be expected for a country with a colder climate like the UK, lower income household groups spend a greater share of their budget on energy. Moreover, the energy expenditure is mostly for residential (heating and lighting) use. As income increases, the share of energy in total expenditure decreases, and spending on fuels for transport increases.

5. Simulation Scenarios

As explained above (Section 3), the aim of the simulations in this paper is consider the general effects of delivering increased energy efficiency in different household income groups. For this reason, we focus on specifying and explaining simple and transparent scenarios, rather than attempting to detail and conduct simulations of particular policy options. We derive the impact of an illustrative 10% improvement in household residential energy use by exploring three main Scenarios. Each scenario is divided into two sub-scenarios: first, *a*, where we assume that the energy efficiency improvement occurs in all households, regardless of their income; then, *b,* where we assume that efficiency improves only in the energy use of the lowest income quintile household. From above, the latter case is identified as a priority focus for public spending where energy poverty is an issue of policy concern.

In Scenario 1 we explore the impact of a 10% costless (and exogenously determined) improvement in household residential energy efficiency. This builds on the work of Lecca et al. (2014), extending that analysis to explore how the implications of the efficiency enhancement differ across the five income quintiles, and focussing only on energy used for heating and lighting (i.e. excluding refined fuel used in personal transportation).

In Scenarios 2 and 3 we consider in broad terms different options for how Government may fund the increase in energy efficiency. Given that we do not have information about the likely cost of increasing household energy efficiency by 10% in UK, we simplify by assuming that the Government compensates for the difference in household energy expenditure before and after the efficiency increase, for a limited time period (5 years). This is done by including in the expenditure items of its own budget, as shown in Equation (6).

$$\overline{GOVBAL_T} = GY_t - GEXP_T + \Delta EC_t \tag{6}$$

In order to keep the budget balanced when EC varies, the Government can either reduce its current expenditure, GEXP, or increase its income, GY, by varying the income tax rate τ. In the sixth period (year) after the efficiency improvement, we consider that it has been completely paid for and Equation (6) is replaced by its standard version described in (5).[16]

Following this approach, in Scenario 2 we assume that a 10% household energy efficiency enhancement is funded via a temporary reallocation of Government spending. This effectively means that for five years the Government has to decrease its expenditure on other goods and services in order to spend on energy efficiency, while ensuring that the government balance is maintained in each period.

[16] Again, we note that this is a simplifying assumption (and, unless the change in expenditure or tax is permanent, the number of periods assumed does not qualitatively impact our results below).

In Scenario 3 we assume that a 10% household energy efficiency improvement is funded through a temporary rise in income tax. This implies that the Government is able to hold its current spending constant while balancing the budget through additional revenue. The focus on income tax is motivated in terms of the energy efficiency improvement being beneficial to households so that paying through tax provides an indirect way of having the household sector as a whole pay for increased efficiency in dwellings. However, there are distributional implications because higher income households pay more tax. Moreover, where only the lowest income household benefits from the energy efficiency improvement, the implication is that this is largely paid for by other households. In terms of the impacts on any economic expansion, introducing a change in income tax has important implications. This is because it triggers a change in supply side behaviour through the wage bargaining process, given that the after-tax or take-home wage, which is the focus of the bargaining process, is directly impacted.

6. Results

6.1. Costless improvement in household energy efficiency

Table 3 shows the short and long-run impacts on key macroeconomic and energy use variables of a costless 10% increase in UK household energy efficiency for the two sub-scenarios: *a*. where the energy efficiency improvement occurs in all households (All HG); *b.* where efficiency improves only in the energy use of the lowest income quintile households (HG1).

We report the results as percentage changes from the base year (SAM 2010) values, with the short-run results referring to the first period (year) after the energy efficiency improvement takes place and the long-run referring to a conceptual time period where the capital stock is fully adjusted to a new steady-state equilibrium. Remember from Section 4 that we assume a fixed national labour supply, with a pool of unemployed labour and wage bargaining where there is a negative relationship between the unemployment rate and real after tax wage.

Beginning with Scenario 1a, where all UK households increase efficiency in residential energy, the first column in Table 3 shows that in the short run the switch in household expenditure away from spending on energy for heating and lighting towards other types of consumption has a small expansionary impact on the economy. Total GDP, consumption (disposable income after savings), employment, and investment increase by 0.03%, 0.52%, 0.05% and 1.14% respectively. As the sectors involved (directly or indirectly) in supplying goods and services where demand has increased expand (off-set by contractions in energy supply chains), there is a corresponding stimulus to labour demand. This causes the unemployment rate to decrease by 0.82% while the nominal wage increases by 0.42%, which, with a CPI increase of 0.32%, equates to the 0.09% increase in the real wage. However, the increase in the CPI does lead to a decrease in total export demand of 0.49% while imports increase by 0.7%.

Total household residential energy consumption falls by 2.35%, which, taking into account how a full range of economy-wide adjustments impact household income and consumption, is a large (76.5%) rebound on the 10% potential energy savings. That total household energy rebound is higher reflects increased spending on refined fuels for personal transportation. However, that the full economy-wide rebound is proportionately smaller (just under 69.9%) reflects that there is a net decrease in energy use on the production side of the economy (due to the contraction in energy supply activity).

The long-run results for Scenario 1a, reported in the second column in Table 3, show household energy use remaining below its base-year value. That rebound effects are smaller in the long-run than in the short-run reflects the impact of 'disinvestment' (Turner, 2009), or contraction in capacity, in energy supply on energy prices and consumption and production choices. There is a further (less energy-intensive) expansion in GDP, with a long run increase of 0.16%. The expansion in the long run is greater than in the short run because the ability for all production sectors to adjust capacity allows a greater response to the net positive demand stimulus from increase real household income reallocated to other goods and services. However, given that the total labour force is assumed to be fixed, there is a fall in the unemployment rate generating an increase in the real wage. This, in turn, puts continued (but declining) upward pressure on all commodity prices and reduces competitiveness so that there is a lasting decrease in export demand (-0.37%).

Table 3. % change in key macrocosmic variables from a 10% costless increase in household residential energy efficiency

	Scenario 1a		**Scenario 1b**	
	SR	**LR**	**SR**	**LR**
GDP	0.03	0.16	0.00	0.02
CPI	0.32	0.21	0.03	0.01
Investment	1.14	0.79	0.15	0.11
Unemployment rate	-0.82	-2.08	0.04	-0.13
Employment	0.05	0.13	0.00	0.01
Nominal wage	0.42	0.45	0.02	0.03
Import	0.70	0.58	0.07	0.05
Export	-0.49	-0.37	-0.04	-0.02
Total energy use	-0.67	-0.89	-0.09	-0.11
Disposable income (excluding savings)	0.52	0.58	0.06	0.07
Household total energy consumption	-1.66	-1.87	-0.22	-0.24
Residential energy consumption	-2.35	-2.62	-0.30	-0.33
Household rebound in res. energy	76.53	73.82	79.03	76.71
Household rebound in total energy	78.89	76.33	80.65	78.50
Economy wide rebound	69.86	59.68	71.94	63.91

The third and fourth columns of Table 3 show the corresponding results if we limit the increase in energy efficiency to the lowest income quintile, Household Group 1 (HG1). The long-run results are qualitatively the same as found in Scenario 1a, but the scale of both the economic expansion and the contraction in total household energy use is much smaller. In the short-run, crowding out effects impacting exports and disinvestment in the energy supply sectors actually causes a very small net negative impact in GDP (-0.001%).[17] The core issue is that the lowest income quintile, where spending power is directly boosted by the energy efficiency improvement, is only a very small source of consumption expenditure in the UK economy. This group is also not a huge beneficiary of increased labour and capital income when the expansion occurs. This means that further induced 'multiplier'

[17] However, sensitivity analysis shows that if the proportionate increase in energy efficiency is larger, here 14%, this is sufficient to make the short-run increase in GDP slightly positive (0.003%, but with the long-run impact, although very slightly larger, remaining the same to the two decimal places in Table 3).

rounds of spending come largely from the other household income groups, and this is limited in the very small expansion reported.[18]

Indeed if we refer to the long-run results for the change in household disposable income net of savings (i.e. consumption spending) in Tables 4a and 4b, note that around 85% of the increase enjoyed by HG1 when energy efficiency improves in all households is retained in the case where only HG1 Increases its efficiency. On the other hand, comparison of the GDP results in the second and fourth columns of Table 3 show that the long-run GDP increase under Scenario 1b is only around 10% of what is realised when all households improve their energy efficiency.

[18] We have run alternative simulations where the other income quintiles are in turn each the recipients of the energy efficiency increase. In all other cases the positive stimulus from their boosted and reallocated spending is sufficient to generate a positive expansion from the outset.

Table 4. % change in household income and energy expenditure in Scenarios 1a and b

	HG1		HG2		HG3		HG4		HG5	
	SR	**LR**	**SR**	**LR**	**SR**	**LR**	**SR**	**LR**	**SR**	**LR**
					Scenario 1a					
Disposable income (excluding savings)	0.70	0.70	0.60	0.63	0.54	0.60	0.51	0.60	0.43	0.52
Residential energy consumption	-1.99	-2.31	-2.19	-2.49	-2.34	-2.61	-2.44	-2.68	-2.61	-2.86
Share of income spent on res. energy	-2.67	-2.99	-2.78	-3.10	-2.87	-3.19	-2.93	-3.26	-3.03	-3.36
Household rebound in residential energy	80.11	76.85	78.07	75.08	76.59	73.87	75.61	73.24	73.90	71.43
	HG1		**HG2**		**HG3**		**HG4**		**HG5**	
	SR	**LR**	**SR**	**LR**	**SR**	**LR**	**SR**	**LR**	**SR**	**LR**
					Scenario 1b					
Disposable income (excluding savings)	0.60	0.60	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.02
Residential energy consumption	-2.41	-2.45	0.05	0.01	0.05	0.02	0.05	0.02	0.05	0.03
Share of income spent on res. energy	-3.00	-3.04	0.04	0.00	0.04	0.00	0.04	0.00	0.04	0.00
Household rebound in residential energy	75.86	75.47	-	-	-	-	-	-	-	-

Comparison of the results in scenarios 1a and 1b reported in Table 4 show that residential energy use in the lowest household income group falls most, as does the share of consumption spending on this energy use, when the efficiency improvement is targeted only in HG1. This is because the rebound in energy use is smaller where there is a more limited boost to household income. However, Table 3 has shown that the total reduction in UK households and economy-wide energy use is smaller (i.e. rebound is larger) under Scenario 1b when the efficiency improvement is limited to HG1. This is because the other households do not experience an improvement in efficiency and slightly increase their energy consumption with the (very limited) economic expansion.

We have run a sensitivity Scenario where each of the household group is in turn the recipient of the 10% increase in energy efficiency. A full set of results is reported in Table C.1, Appendix C. The macroeconomic stimulus is very similar across the five scenarios, with a slightly higher increase in GDP associated with the highest income groups. However, the nature of the change in income and energy consumption is qualitatively similar to what we observe in Scenario 1b. Clearly the gains in terms of income are smaller in each case, because a smaller group of households benefit from the more efficient energy use.

The conclusion that can be drawn is that more extensive energy efficiency stimuli can deliver a fuller set of desired outcomes. This includes achieving reductions in energy use through energy efficiency and (by implication from reduced energy use) carbon reduction targets, boosting household income in low (and other) income households, along with wider economic expansion. However, so far we have not given any consideration to how increased energy efficiency may be funded. Therefore, in the next section, we report on extended simulations where we incorporate a basic consideration of the impacts of applying some treatment of cost via the public budget.

6.2. Basic options for funding improvements in household energy efficiency via the Government budget

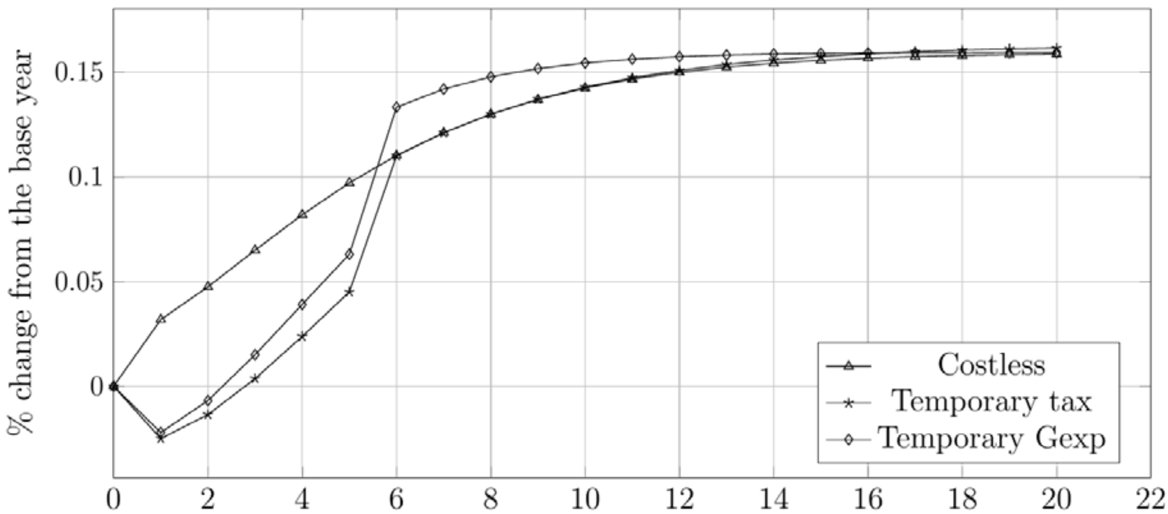
First, let us consider the case of effecting some payment for the introduction of the energy efficiency improvement through a temporary reallocation of government expenditure,[19] in the manner detailed above in Section 5 (Scenarios 2a and 2b).[20] The main impact of the required reduction in Government spending in other areas of the economy is a short run contraction in economic activity (reflected in the GDP results over time in Figure 3). The contraction in activity actually continues for less than the assumed 5-year period of required reallocation of government expenditure. This is because firms are forward looking (i.e. they know that the contraction in spending will end) and they adjust their investment plans accordingly.

At the level of the different household income groups, in Scenario 2a, where all households improve their energy efficiency, the short-run impact is a slightly smaller boost to consumption (disposable income net of savings) but with the gap relative to the 'no cost' Scenario 1a being larger in higher income groups where labour and capital incomes are more important. In Scenario 2b, where energy efficiency only increases in the lowest income quintile, the impact for HG1 remains more or less unchanged relative to Scenario 1b. However, all other groups now experience a slight contraction in their income used for consumption.

[19] Tables C.2 to C.5, Appendix C report the full set of results. However, here we limit our comments to the key differences between Scenarios.
[20] The long run results under Scenarios 2 and 3 are generally not very different to what is observed in Scenario 1 so we do not provide equivalent tables, instead focussing on key results in the figures below.

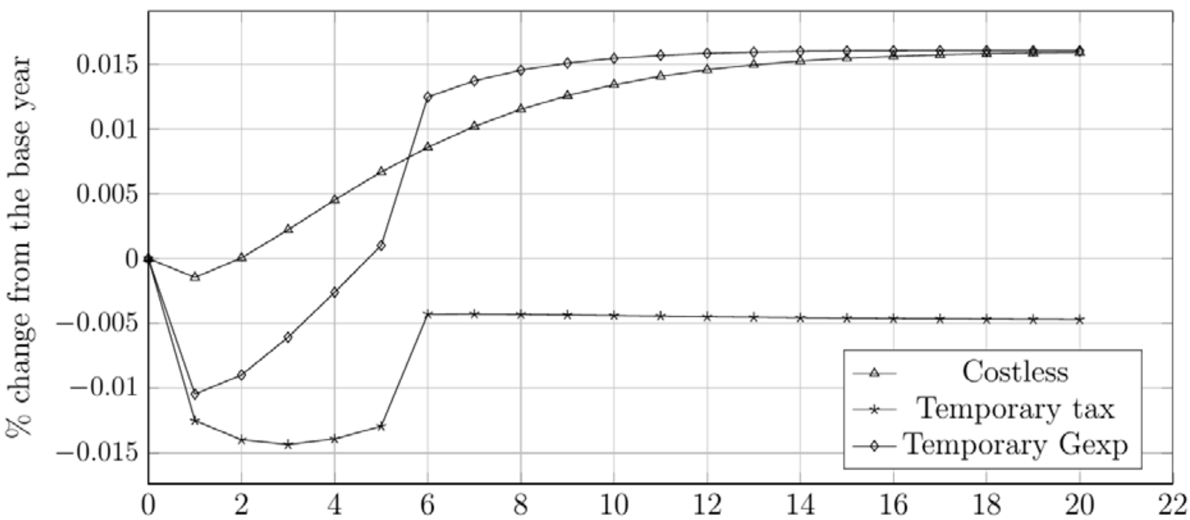
The key finding, however, is that the long-run results under Scenarios 2a and 2b are unchanged relative to the costless case in Scenarios 1a and 1b.

Figure 3: Period by period % change in GDP from a 10% energy efficiency increase in all households



On the other hand, when we consider the case of a temporary increase in the income tax rate (Scenarios 3a and 3b) there are more marked changes in the nature of the results. First, as noted in Section 5, the change in income tax brings about a change in the supply side of the economy. This is because the increase in taxation reduces the take home wage, causing workers to demand higher salaries, putting upward pressure on the real wage and thereby impacting costs faced by all firms. While Figure 3 shows a very close convergence in long-run GDP under Scenario 3a, there are some minor differences in the long-run impacts on GDP, investment and employment/unemployment.

Figure 4: Period by period % change in GDP from a 10% energy efficiency increase in household quintile 1

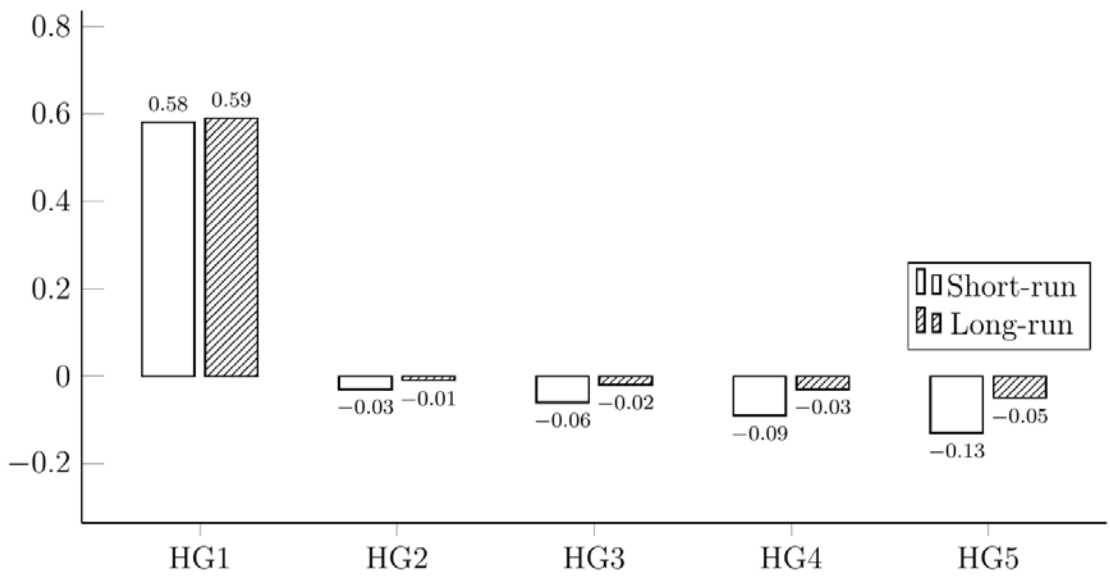


However, there is a greater impact on results when the energy efficiency improvement is limited to HG1 in Scenario 3b. First, Figure 4 shows that there is a small contraction in GDP that lasts into the long run (-0.005%). This implies that the increase in energy efficiency in HG1 does not provide a sufficient economic stimulus to demand to deliver a long-run expansion in the presence of the adverse supply-side shock that is delivered via the induced rise in wage demands.[21]

Moreover, while the impact on income used for consumption is very similar in Scenario 3b (as compared to 3a) under the government spending and tax options for HG1 (only slightly worse under the latter), it is very different for all the other household income groups. Initially, given that they pay more income tax, HG2-5, effectively pay for the increase in HG1 energy efficiency through their increased tax contributions. However, over time, even once the tax rate returns to its original level, the other groups continue to pay through the greater impact on their disposable (net of savings) incomes from the economic contraction. This is shown in Figure 5. Note that the biggest 'loser' is the highest income quintile, HG5. This is due to the fact that income from ownership of capital (most important in HG5) is adversely affected in this scenario due to more limited investment activity.

We have run a specific sensitivity scenario where we increase the size of the energy efficiency improvement in HG1 to see what is required to produce a positive GDP result over the long-run under the income tax funding scenario. We find that a 12% boost to the residential energy use in HG1 is sufficient to deliver a net positive (0.0003%) increase in GDP over the long run, with the positive result emerging from period 11. However, the net negative impact on disposable income in the other household groups persists, albeit to a lesser extent. We find that, where we have an income tax funding arrangement as above, a doubling of the efficiency improvement in HG1 residential energy use to 20% is required to remove the long-run negative impacts on the disposable income of all other groups. Below this, the highest income household remains most affected, for example with only HG5 losing out over the long run where the efficiency improvement in HG1 is 19%.

Figure 5: Short-run and long-run percentage change in disposable income from a 10% household energy efficiency increase funded via an increase in income tax



Overall, the results above suggest that imposing a cost for increasing energy efficiency via the public budget will constrain the 'multiple benefits' of increased energy efficiency at least in the shorter run.

[21] However, again, we find that if any other household group is the sole beneficiary of the energy efficiency improvement, the resulting stimulus is sufficient to deliver a net expansion in GDP, and that this is more so the higher the income level of the group in question.

However, if the economic expansion is sufficiently big, the long-run outcome is one of net gain in broader economic impacts. When the efficiency improvement is targeted only in the lowest income households this does deliver the desired outcomes for that group, but it weakens the economic expansion, while the need for (and nature of) public funding through the government budget becomes much more important.

7. Conclusions and policy implications

Many recent economic modelling studies of increased energy efficiency have tended to focus on the issue of rebound effects. However, in considering economy-wide rebound in particular, some studies have identified economic expansion resulting from increased energy efficiency as the driver of rebound, a finding that is consistent with the type of 'Multiple Benefits' argument proposed by the IEA (2014). Here, we have focused our attention on how the economic expansion may provide a justification for public/government support of energy efficiency programmes.

Specifically, we have used an illustrative CGE modelling analysis for the UK to consider the general effects of government support of domestic energy efficiency programmes. We have raised the question of whether only low income households should be aided in improving their energy efficiency, or whether there is sufficient return through expansion to justify potentially supporting wider ranging programmes. A key point that we have raised is that many governments are committed to the support of energy efficiency programmes but may focus this in low income households. However, Governments tend to have a wider set of desired outcomes, including reduced energy use and carbon emissions, but also in terms of reducing poverty (including but not limited to energy poverty) and increasing economic well-being, in part through GDP and employment growth.

In considering scenarios where support is provided only for the lowest income households to increase their energy efficiency, our findings suggest that it is likely to be difficult to meet all of government's objectives simultaneously through limited support of households that are significantly less connected to the wider economy than others (in terms of their level of spending and their sources of income). Our own results suggest that in order to stimulate economic activity by this route quite large proportionate increases in residential energy efficiency in low income household need to be achieved. In contrast, where the introduction of increased energy efficiency is spread over all (or at least a wider range) of households, even where there is a cost to supporting energy efficiency improvements, the return via the impacts of economic expansion is likely to provide what justification for support.

However, our findings suggest that the means of providing support for energy efficiency programmes should be carefully considered and examined. Our results imply that a reallocation of government spending will be less distortive than requiring the household sector to pay indirectly (according to ability to pay) via income tax. However, we reserve fuller consideration of specific funding mechanisms for future research, ideally in consultation with policy decision makers particularly within the UK.

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Appendix A. Industries included in the UK-ENVI model

Table 1.A. List of production sectors in the UK- ENVI model, corresponding sectors in the 2010 UK IO tables, Standard Industrial Classification (SIC) codes.

Sector name	SIC
Agriculture, forestry and fishing	01-03.2
Mining and quarrying	05
Crude petroleum and natural gas + coal	06-08
Other Mining and mining services	09
Food (and tobacco)	10.1-10.9,12
Drink	11.01-11.07
Textile, leather, wood	13-16
Paper and printing	17-18
Coke and refined petroleum products	19-20B
Chemicals and pharmaceuticals	20.3-21
Rubber, cement, glass	22-23other
Iron, steel and metal	24.1-25
Electrical manufacturing	26-28
Manufacture of motor vehicles, trailers etc.	29
Transport equipment and other manufacturing	30-33
Electricity, transmission and distribution	35.1
Gas distribution	35.2-35-3
Water treatment and supply and sewerage	36-37
Waste management and remediation	38-39
Construction-Buildings	41-43
Wholesale and retail trade	45-47
Land and transport	49.1-49.2
Other transport	49.3-51
Transport support	52-53
Accommodation and food and services	55-56,58
Communication	59-63
Services	64-82,97
Education health and defence	84-88
Recreational	90-94
Other private services	95,97

Appendix B. Disaggregation of 2010 UK SAM household sector

For the purposes of this work, we disaggregate the 2010 UK SAM household sector by income quintiles[22], following the approach adopted by the UK Office for National Statistics (ONS) in its Family Spending publication, which reports the findings of the Living Costs and Food Survey (LCFS; Office for National Statistics 2011, 2012, 2013). Each of the quintiles refer the weekly gross income reported in Table 2 in Section 4.3.

We disaggregate the UK SAM in three distinct steps: 1) disaggregation of household spending on goods and services (via the IO tables incorporated in the SAM); 2) disaggregation of non-IO household expenditure and of income; 3) rebalance of the SAM.

1. The 2010 Input Output reports household expenditure on the outputs of each of the 104 production sectors included in the UK tables. To disaggregate household consumption we use information from the LCFS, which reports household consumption for different income group. To avoid any errors that could be driven by the sample size and/or the socio-economic conditions during a specific year, we use 3-year average figures from 2009 to 2011 (Office from National Statistics 2011, 2012, 2013). We map the 12 spending categories reported in the table of derived household variables from the LCFS to the household final consumption expenditure (HHFCe) which is included in the IO table. This allows us to calculate for each spending category, the proportion of each income quintile's expenditure on each group. Finally, we multiply the shares of each quintile's expenditure by the household consumption as reported in the UK SAM to obtain a disaggregated picture of the household final consumption for each of the quintiles and each of the SAM sectors.
2. In addition to the IO table, the 2010 UK SAM includes information on income transfers not included in the IO accounts drawn from elsewhere in the UK national accounts. We again use the LCFS to disaggregate household income from different sources, including the employment and capital income that are reflected (to some extent in the IO data) and transfers to and from government and non-government institutions, corporations, the rest of the world, and the capital accounts. As in the first step, we again use figures averaged over three years (Office from National Statistics 2011, 2012, 2013).
3. Disaggregating household income and expenditure leads to imbalances within each of the household quintiles. Therefore, it is necessary to manually re-balance the SAM so that we do not disrupt the integrity of the rest of the matrix. We do so by allocating any discrepancies between the rows and the columns of each quintile to the capital formation (savings/borrowing) entry for each quintile.

[22] The UK Family Spending survey reports deciles so we must merge over pair of deciles to create quintiles.

Appendix C: additional tables of results from simulation

Table C1. Percentage change in household income and energy expenditure from a 10% costless residential energy efficiency improvement in each household group individually

	HG1		HG2		HG3		HG4		HG5	
	SR	**LR**	**SR**	**LR**	**SR**	**LR**	**SR**	**LR**	**SR**	**LR**
Macroeconomic impacts										
GDP	0.00	0.02	0.00	0.02	0.00	0.03	0.00	0.03	0.00	0.03
Consumer Price Index	0.03	0.01	0.05	0.02	0.05	0.03	0.05	0.03	0.06	0.03
Investment	0.15	0.11	0.20	0.15	0.23	0.17	0.23	0.17	0.25	0.18
Unemployment Rate	0.04	-0.13	-0.02	-0.25	-0.04	-0.29	-0.04	-0.30	-0.08	-0.35
Total Employment	0.00	0.01	0.00	0.02	0.00	0.02	0.00	0.02	0.01	0.02
	HG1		**HG2**		**HG3**		**HG4**		**HG5**	
	SR	**LR**	**SR**	**LR**	**SR**	**LR**	**SR**	**LR**	**SR**	**LR**
Household energy consumption										
Disposable income (excluding savings)	0.60	0.60	0.50	0.51	0.42	0.43	0.35	0.37	0.26	0.28
Residential energy consumption	-2.41	-2.45	-2.60	-2.65	-2.76	-2.82	-2.89	-2.94	-3.07	-3.13
Share of income spent on res. energy	-19.84	-20.19	-16.73	-17.15	-14.01	-14.42	-11.92	-12.28	-8.51	-8.79
Household rebound in residential energy	75.86	75.47	74.02	73.49	72.39	71.83	71.13	70.61	69.34	68.68

Table C.2. Scenario 2. Percentage change in key macroeconomic variables from a 10% residential energy efficiency increase funded via Government spending reallocation

	Scenario 2a		Scenario 2b	
	SR	LR	SR	LR
GDP	-0.02	0.16	-0.01	0.02
CPI	0.17	0.21	0.00	0.01
Investment	1.26	0.79	0.17	0.11
Unemployment rate	0.55	-2.08	0.27	-0.13
Employment	-0.04	0.13	-0.02	0.01
Nominal wage	0.11	0.45	-0.03	0.03
Import	0.43	0.58	0.02	0.05
Export	-0.26	-0.37	0.00	-0.02
Government expenditure	-0.86	0.01	-0.21	-0.08
Total energy use	-0.74	-0.89	-0.10	-0.11
Disposable income (excluding savings)	0.38	0.58	0.04	0.07
Household total energy consumption	-1.83	-1.87	-0.24	-0.24
Household residential energy	-2.51	-2.62	-0.32	-0.33
Household rebound residential energy	74.92	73.82	77.07	76.71
Household rebound in total energy	76.85	76.33	78.18	78.50
Economy wide rebound	66.31	59.68	67.68	63.91

Table C.3. Percentage change in household income and energy expenditure in Scenarios 2a and b

	HG1		**HG2**		**HG3**		**HG4**		**HG5**	
	SR	**LR**	**SR**	**LR**	**SR**	**LR**	**SR**	**LR**	**SR**	**LR**
					Scenario 2a					
Disposable income (excluding savings)	0.64	0.70	0.52	0.63	0.42	0.60	0.34	0.60	0.27	0.52
Residential energy consumption	-2.09	-2.31	-2.31	-2.49	-2.50	-2.61	-2.64	-2.68	-2.81	-2.86
Share of income spent on res. energy	-2.71	-2.99	-2.82	-3.10	-2.90	-3.19	-2.97	-3.26	-3.08	-3.36
Household rebound in residential energy	79.13	76.85	76.86	75.08	75.04	73.87	73.62	73.24	71.86	71.43
	HG1		**HG2**		**HG3**		**HG4**		**HG5**	
	SR	**LR**	**SR**	**LR**	**SR**	**LR**	**SR**	**LR**	**SR**	**LR**
					Scenario 2b					
Disposable income (excluding savings)	0.59	0.60	-0.01	0.01	-0.01	0.01	-0.02	0.02	-0.02	0.02
Residential energy consumption	-2.43	-2.45	0.03	0.01	0.02	0.02	0.02	0.02	0.02	0.03
Share of income spent on res. energy	-3.00	-3.04	0.04	0.00	0.04	0.00	0.04	0.00	0.04	0.00
Household rebound in residential energy	75.69	75.47	-	-	-	-	-	-	-	-

Table C.4. Scenario 3. Percentage change in key macroeconomic variables from a 10% residential energy efficiency increase funded via income tax rate variation

	Scenario 3a		**Scenario 3b**	
	SR	**LR**	**SR**	**LR**
GDP	-0.02	0.16	-0.01	0.00
CPI	0.17	0.21	-0.01	0.02
Investment	0.68	0.81	-0.03	0.01
Unemployment rate	0.63	-2.12	0.32	0.09
Employment	-0.04	0.14	-0.02	-0.01
Nominal wage	0.095	0.452	-0.04	-0.03
Import	0.29	0.58	-0.03	0.02
Export	-0.25	-0.37	0.01	-0.03
Income tax rate	0.97	-0.02	0.24	0.24
Total energy use	-0.85	-0.89	-0.13	-0.14
Disposable income (excluding savings)	0.11	0.59	-0.04	0.02
Household total energy consumption	-2.05	-1.86	-0.31	-0.28
Household residential energy	-2.71	-2.61	-0.38	-0.37
Household rebound residential energy	72.86	73.89	72.96	73.96
Household rebound in total energy	74.03	76.43	72.65	74.83
Economy wide rebound	61.64	59.92	58.51	54.45

Table C.5. Percentage change in household income and energy expenditure in Scenarios 3a and b

	HG1		HG2		HG3		HG4		HG5	
	SR	**LR**	**SR**	**LR**	**SR**	**LR**	**SR**	**LR**	**SR**	**LR**
					Scenario 3a					
Disposable income (excluding savings)	0.60	0.70	0.42	0.63	0.23	0.60	0.08	0.61	-0.17	0.53
Residential energy consumption	-2.12	-2.31	-2.39	-2.49	-2.67	-2.61	-2.88	-2.67	-3.22	-2.84
Share of income spent on res. energy	-2.70	-3.00	-2.81	-3.10	-2.89	-3.19	-2.96	-3.26	-3.06	-3.36
Household rebound in residential energy	78.79	76.87	76.05	75.12	73.29	73.93	71.20	73.33	67.79	71.55
	HG1		**HG2**		**HG3**		**HG4**		**HG5**	
	SR	**LR**	**SR**	**LR**	**SR**	**LR**	**SR**	**LR**	**SR**	**LR**
					Scenario 3b					
Disposable income (excluding savings)	0.58	0.59	-0.03	-0.01	-0.06	-0.02	-0.09	-0.03	-0.13	-0.05
Residential energy consumption	-2.44	-2.46	0.00	0.00	-0.03	-0.02	-0.05	-0.03	-0.09	-0.04
Share of income spent on res. energy	-3.00	-3.04	0.04	0.00	0.04	0.00	0.04	0.00	0.04	0.00
Household rebound in residential energy	75.56	75.37	-	-	-	-	-	-	-	-

Appendix D. The mathematical presentation of the UK-ENVI model

Prices

$$PM_{i,t} = \overline{PM}_i \tag{D.1}$$

$$PE_{i,t} = \overline{PE}_i \tag{D.2}$$

$$PQ_{i,t} = \frac{PR_{i,t} \cdot R_{i,t} + PM_{i,t} \cdot M_{i,t}}{R_{i,t} + M_{i,t}} \tag{D.3}$$

$$PIR_{j,t} = \frac{\sum_i VR_{i,j,t} \cdot PR_{j,t} + \sum_i VI_{i,j,t} \cdot \overline{PI}_j}{\sum_i VIR_{i,j,t}} \tag{D.4}$$

$$PY_{j,t} \cdot Y_{j,t} = PX_{j,t} \cdot X_{j,t} - \sum_i PQ_{j,t} \cdot VV_{i,j,t} - IBT_{i,t} \tag{D.5}$$

$$UCK_t = Pk_t \cdot (r + \delta) \tag{D.6}$$

$$Pc_t^{1-\sigma^c} = \sum_j \delta_j^f \cdot PQ_{j,t}^{1-\sigma^c} \tag{D.7}$$

$$Pg_t^{1-\sigma^g} = \sum_j \delta_j^g \cdot PQ_{j,t}^{1-\sigma^g} \tag{D.8}$$

$$PNE_t = \frac{\sum_z PQ_{z,t} \cdot \bar{V}_z}{\sum_z PQ_z \cdot \bar{V}_z} \tag{D.9}$$

$$PE_t = \frac{\sum_E PQ_{E,t} \cdot \bar{V}_E}{\sum_E PQ_E \cdot \bar{V}_E} \tag{D.10}$$

$$w_t^b = \frac{w_t}{(1 + \tau_t)} \tag{D.11}$$

$$ln\left(\frac{w_t^b}{cpi_t}\right) = \varphi - 0.068\, ln(u_t) \tag{D.12}$$

$$rk_{j,t} = PY_{j,t} \cdot \delta_j^k \cdot A^{Y\varrho_j} \cdot \left(\frac{Y_{j,t}}{K_{j,t}}\right)^{1-\varrho_j} \tag{D.13}$$

$$Pk_t = \frac{\sum_j PQ_{j,t} \cdot \sum_i KM_{i,j}}{\sum_i \sum_j KM_{i,j}} \tag{D.14}$$

Production technology

$$X_{i,t} = A_i{}^X \cdot \left[\delta_i^Y \cdot Y_{i,t}^{\rho_i^X} + (1-\delta_i^V) \cdot V_{i,t}^{\rho_i^X}\right]^{\frac{1}{\rho_i^X}} \quad \textbf{(D.15)}$$

$$Y_{j,t} = \left(A^{X\rho_j^X} \cdot \delta_j^Y \cdot \frac{PQ_{j,t}}{PY_{j,t}}\right)^{\frac{1}{1-\rho_j^X}} \cdot X_{j,t} \quad \textbf{(D.16)}$$

$$V_{j,t} = \left(A^{X\rho_j^X}\left(1-\delta_j^V\right) \cdot \frac{PQ_{j,t}}{Pv_{j,t}}\right)^{\frac{1}{1-\rho_j^X}} \cdot X_{j,t} \quad \textbf{(D.17)}$$

$$V_{j,t} = A^V \cdot \left[\delta_i^V \cdot E_{i,t}^{\rho_i^V} + (1-\delta_i^V) \cdot NE_{i,t}^{\rho_i^V}\right]^{\frac{1}{\rho_i^V}} \quad \textbf{(D.18)}$$

$$\frac{E_{j,t}}{NE_{j,t}} = \left[\left(\frac{\delta_j^V}{(1-\delta_j^V)}\right) \cdot \left(\frac{PNE_t}{PE_t}\right)\right]^{\frac{1}{1-\rho_i^V}} \quad \textbf{(D.19)}$$

$$VV_{z,j,t} = \left(A^{z\rho_j^z}\left(1-\delta_j^{EN}\right) \cdot \frac{PNE_t}{PQ_{z,t}}\right)^{\frac{1}{1-\rho_j^Z}} \cdot NE_{j,t} \quad \textbf{(D.20)}$$

$$VV_{E,j,t} = \left(A^{E\rho_j^E}\left(\delta_j^{EN}\right) \cdot \frac{PE_t}{PQ_{E,t}}\right)^{\frac{1}{1-\rho_j^E}} \cdot E_{j,t} \quad \textbf{(D.21)}$$

$$Y_{i,t} = A^Y \cdot \left[\delta_i^k \cdot K_{i,t}^{\rho_i^Y} + \delta_i^l \cdot L_{i,t}^{\rho_i^Y}\right]^{\frac{1}{\rho_i^Y}} \quad \textbf{(D.22)}$$

$$L_{j,t} = \left(A^{Y\rho_j^Y} \cdot \delta_j^l \cdot \frac{PY_{j,t}}{w_t}\right)^{\frac{1}{1-\rho_j^Y}} \cdot Y_{j,t} \quad \textbf{(D.23)}$$

Trade

$$VV_{i,j,t} = \gamma_{i,j}^{vv} \cdot \left[\delta_{i,j}^{vm} VM_{i,t}^{\rho_i^A} + \delta_{i,j}^{vir} VIR_{i,t}^{\rho_i^A}\right]^{\frac{1}{\rho_i^A}} \quad \textbf{(D.24)}$$

$$\frac{VM_{i,j,t}}{VIR_{i,j,t}} = \left[\left(\frac{\delta_{i,j}^{vm}}{\delta_{i,j}^{vir}}\right) \cdot \left(\frac{PIR_{i,t}}{PM_{i,t}}\right)\right]^{\frac{1}{1-\rho_i^A}} \quad \textbf{(D.25)}$$

$$VIR_{i,j,t} = \gamma_{i,j}^{vir} \cdot \left[\delta_{i,j}^{vi} VI_{i,t}^{\rho_i^A} + \delta_{i,j}^{vr} VR_{i,t}^{\rho_i^A}\right]^{\frac{1}{\rho_i^A}} \quad \textbf{(D.26)}$$

$$\frac{VR_{i,j,t}}{VI_{i,j,t}} = \left[\left(\frac{\delta_{i,j}^{vr}}{\delta_{i,j}^{vi}}\right) \cdot \left(\frac{PI_{i,t}}{PR_{i,t}}\right)\right]^{\frac{1}{1-\rho_i^A}} \quad \textbf{(D.27)}$$

$$E_{i,t} = \bar{E}_i \cdot \left(\frac{PE_{i,t}}{PQ_{i,t}}\right)^{\sigma_i^x} \quad \textbf{(D.28)}$$

National Demand

$$R_{i,t} = \sum_j VR_{i,j,t} + \sum_h QHR_{i,h,t} + QVR_{i,t} + QGR_{i,t} \quad \textbf{(D.29)}$$

Total absorption equation

$$X_{i,t} + M_{i,t} = \sum_j VV_{i,j,t} + \sum_h QH_{i,h,t} + QV_{i,t} + QG_{i,t} + E_{i,t} \quad \textbf{(D.30)}$$

Households and other Domestic Institutions

$$YH_{h,t} = SHL_h \cdot LY_t + SHK_h \cdot KY_t \quad \textbf{(D.31)}$$

$$C_{h,t} = YH_{h,t} - S_{h,t} \quad \textbf{(D.32)}$$

$$LY_t = (1 - \tau_t)L_t^s\,(1 - u_t)w_t + Trf_t \quad \textbf{(D.33)}$$

$$KY_t = \Pi_t \quad \textbf{(D.34)}$$

$$Trf_t = Pc_t \cdot \overline{Trf} \quad \textbf{(D.35)}$$

$$S_t = mps \cdot [(1 - \tau_t)L_t^s\,(1 - u_t)w_t + Trf_t] \quad \textbf{(D.36)}$$

$$\Pi_t = \sum_i rk_{i,t}K_{i,t} \quad \textbf{(D.37)}$$

$$C_{h,t} = \left[\delta_h{}^E\left(\gamma_h Ec_{h,t}\right)^{\rho e} + (1 - \delta_h{}^E)NEc_{h,t}^{\rho e}\right]^{\frac{1}{\rho e}} \quad \textbf{(D.38)}$$

$$Ec_{h,t} = \left[\gamma_h{}^{\rho e}\,\delta_h{}^E \cdot \left(\frac{Pc_t}{PE_t}\right)\right]^{\frac{1}{1-\rho e}} C_{h,t} \quad \textbf{(D.39)}$$

$$Ec_{h,t} = \left[\delta_h{}^{co}CO_{h,t}^{\rho g} + (1 - \delta_h{}^{co})EG_{h,t}^{\rho g}\right]^{\frac{1}{\rho g}} \quad \textbf{(D.40)}$$

$$\frac{CO_{h,t}}{EGc_{h,t}} = \left[\left(\frac{\delta_h{}^{co}}{1 - \delta\delta_h{}^{co}}\right) \cdot \left(\frac{PEG_t}{PCO_t}\right)\right]^{\frac{1}{1-\rho g}} \quad \textbf{(D.41)}$$

$$QH_{h,z,t} = \delta_{h,z}^{f}{}^{\rho_i^c} \cdot \left(\frac{Pc_t}{PQ_{z,t}}\right)^{\rho_i^c} \cdot NEc_{h,t} \quad \textbf{(D.42)}$$

$$EG_{h,t} = \left[\delta_h{}^{Ele} Ele_{h,t}^{\rho_{el}} + (1 - \delta_h{}^{el}) GAS_{h,t}^{\rho_{el}}\right]^{\frac{1}{\rho_{el}}} \quad \textbf{(D.43)}$$

$$\frac{Ele_{h,t}}{GAS_{h,t}} = \left[\left(\frac{\delta_h{}^{GAS}}{1 - \delta_h{}^{GAS}}\right) \cdot \left(\frac{PQ_{GAS,t}}{PQ_{Ele,t}}\right)\right]^{\frac{1}{1-\rho_{el}}} \quad \textbf{(D.44)}$$

$$QH_{ele,h,t} = Ec_{h,t} \quad \textbf{(D.45)}$$

$$QH_{GAS,h,t} = GAS_{h,t} \quad \textbf{(D.46)}$$

$$QH_{coal,h,t} = CL_{h,t} \quad \textbf{(D.47)}$$

$$QH_{oil,h,t} = OIL_{h,t} \quad \textbf{(D.48)}$$

$$QH_{i,h,t} = \gamma_{i,h}^{f} \cdot \left[\delta_{i,h}^{hir} \cdot QHIR_{i,h,t}^{\rho_i^A} + \delta_{i,h}^{hm} \cdot QHM_{i,h,t}^{\rho_i^A}\right]^{\frac{1}{\rho_i^A}} \quad \textbf{(D.49)}$$

$$\frac{QHIR_{i,h,t}}{QHM_{i,h,t}} = \left[\left(\frac{\delta_{i,h}^{hir}}{\delta_{i,h}^{hm}}\right) \cdot \left(\frac{PM_{i,t}}{PIR_{i,t}}\right)\right]^{\frac{1}{1-\rho_i^A}} \quad \textbf{(D.50)}$$

$$QHIR_{i,h,t} = \gamma_{i,h}^{fir} \cdot \left[\delta_{i,h}^{hr} \cdot QHR_{i,h,t}^{\rho_i^A} + \delta_{i,h}^{hi} \cdot QHI_{i,h,t}^{\rho_i^A}\right]^{\frac{1}{\rho_i^A}} \quad \textbf{(D.51)}$$

$$\frac{QHR_{i,h,t}}{QHI_{i,h,t}} = \left[\left(\frac{\delta_{i,h}^{hr}}{\delta_{i,h}^{hi}}\right) \cdot \left(\frac{PI_{i,t}}{PR_{i,t}}\right)\right]^{\frac{1}{1-\rho_i^A}} \quad \textbf{(D.52)}$$

Government

$$\overline{FD}_t = GEXP_t - GY_t \quad \textbf{(D.53)}$$

$$GY_t = \left(d^g \cdot \sum_i rk_{i,t} \cdot K_{i,t} + \sum_i IBT_{i,t} + \tau_t \cdot \sum_j L_{j,t} \cdot w_t + \overline{FE} \cdot \varepsilon_t\right) \quad \textbf{(D.54)}$$

$$GEXP_t = G_t \cdot Pg_t + \sum_{dngins} \overline{TRG}_{dngins,t} \cdot CPI_t \quad \textbf{(D.55)}$$

$$QG_{i,t} = \delta_i^g \cdot G_t \quad \textbf{(D.56)}$$

$$QGR_{i,t} = QG_{i,t};\ QGM_{i,t} = 0 \quad \textbf{(D.57)}$$

Investment Demand

$$QV_{i,t} = \sum_j KM_{i,j} \cdot J_{j,t} \quad \textbf{(D.58)}$$

$$QV_{i,t} = \gamma_i^v \cdot \left[\delta_i^{qvm} \cdot QVM_{i,t}^{\rho_i^A} + \delta_i^{qvir} \cdot QVIR_{i,t}^{\rho_i^A}\right]^{\frac{1}{\rho_i^A}} \quad \textbf{(D.59)}$$

$$\frac{QVM_{i,t}}{QVIR_{i,t}} = \left[\left(\frac{\delta_i^{qvm}}{\delta_i^{qvir}}\right) \cdot \left(\frac{PIR_{i,t}}{PM_{i,t}}\right)\right]^{\frac{1}{1-\rho_i^A}} \quad \textbf{(D.60)}$$

$$QVIR_{i,t} = \gamma_i^{vir} \cdot \left[\delta_i^{qvi} \cdot QVI_{i,t}^{\rho_i^A} + \delta_i^{qvr} \cdot QVR_{i,t}^{\rho_i^A}\right]^{\frac{1}{\rho_i^A}} \quad \textbf{(D.61)}$$

$$\frac{QVR_{i,t}}{QVI_{i,t}} = \left[\left(\frac{\delta_i^{qvr}}{\delta_i^{qvi}}\right) \cdot \left(\frac{PI_{i,t}}{PR_{i,t}}\right)\right]^{\frac{1}{1-\rho_i^A}} \quad \textbf{(D.62)}$$

Time path of investment

$$J_{i,t} = I_{i,t}\left(1 - bb - tk + \frac{\beta}{2}\,\frac{\left(\frac{I_{i,t}}{K_{i,t}} - \alpha\right)^2}{\frac{I_{i,t}}{K_{i,t}}}\right) \quad \textbf{(D.63)}$$

$$\frac{I_t}{K_t} = \alpha + \frac{1}{\beta} \cdot \left[\frac{\lambda_{i,t}}{Pk_t} - (1 - bb - tk)\right] \quad \textbf{(D.64)}$$

$$\dot{\lambda}_{i,t} = \lambda_{i,t}(r_t + \delta) - R_{i,t}^k \quad \textbf{(D.65)}$$

$$\theta(x_t) = \frac{\beta}{2}\,\frac{(x_t - \alpha)^2}{x_t};\ \text{and}\ x_t = \frac{I_t}{K_t} \quad \textbf{(D.66)}$$

$$R_{i,t}^k = rk_t - Pk_t\left[\frac{I_{i,t}}{K_{i,t}}\right]^2 \theta'_t(I/K) \quad \textbf{(D.67)}$$

Factors accumulation

$$KS_{i,t+1} = (1-\delta)\cdot KS_{i,t} + I_{i,t} \quad \textbf{(D.68)}$$

$$K_{i,t} = KS_{i,t} \quad \textbf{(D.69)}$$

$$LS_t \cdot (1-u_t) = \sum_j L_{j,t} \quad \textbf{(D.70)}$$

Indirect taxes and subsidies

$$IBT_{i,t} = btax_i \cdot X_{i,t} \cdot PQ_{i,t} \quad \textbf{(D.71)}$$

Total demand for import and current account

$$M_{i,t} = \sum_j VI_{i,j,t} + \sum_j VM_{i,j,t} + \sum_h QHM_{i,h,t} + QGM_{i,t} + QVI_{i,t} + QVM_{i,t} \quad \textbf{(D.72)}$$

$$TB_t = \sum_i M_{i,t}\cdot PM_{i,t} - \sum_i E_{i,t}\cdot PE_{i,t} + \varepsilon \cdot \left(\sum_{dngins} \overline{REM}_{dngins} + \overline{FE}\right) \quad \textbf{(D.73)}$$

Steady State conditions

$$\delta \cdot KS_{i,T} = I_{i,T} \quad \textbf{(D.74)}$$

$$R^k_{i,T} = \lambda_{i,T}(r+\delta) \quad \textbf{(D.75)}$$

In order to produce short-run results, we have that

$$KS_{i,t=1} = KS_{i,t=0} \quad \textbf{(D.76)}$$

$$LS_{=1} = LS_{t=0} \quad \textbf{(D.77)}$$

Glossary

$i,j \quad (i=j)$	the set of goods or industries
ins	the set of institutions
$dins\ (\subset ins)$	the set of domestic institutions
$dngins\ (\subset dins)$	the set of non-government institutions
$h(\subset dngins)$	the set of households
$E\ (\subset i)$	the set of energy sectors {*Coal, Ele, Gas and Oil*}
$z\ (\subset i)$	the set of non-energy sectors

Prices

$PY_{i,t}$	value added price
$PR_{i,t}$	national price
$PQ_{i,t}$	output price
$PIR_{i,t}$	commodity price (national+ REU)
$PI_{i,t}$	price of REU commodities
$rk_{i,t}$	rate of return to capital
w_t	unified nominal wage
w_t^b	after tax wage
Pk_t	capital good price
UCK_t	user cost of capital
$\lambda_{i,t}$	shadow price of capital
Pc_t	aggregate consumption price
Pg_t	aggregate price of Government consumption goods
ε	exchange rate [fixed]

Endogenous variables

$X_{i,t}$	total output
$R_{i,t}$	national supply
$M_{i,t}$	total import
$E_{i,t}$	total export
$Y_{i,t}$	value added
$L_{i,t}$	labour demand
$K_{i,t}$	physical capital demand
$KS_{i,t}$	capital stock

$LS_{i,t}$	labour supply
$VV_{i,j,t}$	total intermediate inputs in *i* and *j*
$V_{i,t}$	Total intermediate inputs in *i*
$VR_{i,j,t}$	national intermediate inputs
$VM_{i,j,t}$	ROW intermediate inputs
$VIR_{i,j,t}$	Aggregate intermediate inputs (ROW+REU)
$VI_{i,j,t}$	ROI intermediate inputs
$GEXP_{i,t}$	aggregate government expenditure
$QG_{i,t}$	total government expenditure by sector *i*
$QGR_{i,t}$	national government expenditure
$IBT_{i,t}$	Indirect business taxes
$QGM_{i,t}$	Government import expenditure
$C_{h,t}$	aggregated household consumption
$Ec_{h,t}$	household consumption of energy
$NEc_{h,t}$	household consumption of non-energy goods and transport
$CO_{h,t}$	household consumption of Coal
$EG_{h,t}$	household consumption of Electricity and Gas
$Ele_{h,t}$	household consumption of Electricity
$GAS_{h,t}$	household consumption of Gas
$QH_{i,h,t}$	total households consumption in sector *i*
$QHR_{i,h,t}$	national consumption in sector *i*
$QHIR_{i,h,t}$	national+REU consumption in sector *i*
$QHM_{i,h,t}$	import consumption in sector *i*
$YH_{h,t}$	Household income
$LY_{i,t}$	Labour income
$KY_{i,t}$	Capital income
SHL_h	Households share of labour income
SHK_h	Households share of capital income
$QV_{i,t}$	total investment by sector of origin *i*
$QVR_{i,t}$	national investment by sector of origin *i*
$QVM_{i,t}$	ROW investment demand
$QVIR_{i,t}$	national investment (national+REU)
$QVI_{i,t}$	ROI investment demand
$I_{j,t}$	investment by sector of destination *j*
$J_{j,t}$	investment by destination *j* with adjustment cost
u_t	national unemployment rate
$R^k_{i,t}$	marginal net revenue of capital

S_t	domestic non-government saving
Trf_t	households net transfer
$TRSF_{dngins,dnginsp,t}$	transfer among *dngins*
$\overline{TRG}_{dngins,t}$	Government's transfer to *dngins*
$HTAX_t$	total household tax
TB_t	current account balance

Exogenous variables

$\overline{REM}_t$	remittance for *dngins*
$\overline{FE}_t$	remittance for the Government
$GSAV_t$	government saving
r	interest rate

Elasticities

σ	constant elasticity of marginal utility
ρ_i^X	elasticity parameter between intermediate inputs and value added
ρ_i^Y	elasticity parameter between capital and labour
ρ_i^A	in Armington function
σ_i^x	of export with respect to term of trade
σ_i^e	Substitution between energy and non-energy in Household consumption
σ_i^g	Substitution elasticity between CO and EG in Household consumption
σ_i^o	Substitution elasticity between Coal and Oil in Household consumption

Parameters

$a_{i,j}^V$	Input-output coefficients for *i* used in *j*
a_j^Y	share of value added on production
$\delta_j^{Y,V}$	shares in CES output function in sector *j*
$\delta_j^{k,l}$	shares in value added function in sector *j*
$\delta_{i,j}^{vir,vm,vr,vi}$	shares parameters in CES function for intermediate goods
$\delta_{i,j}^{qvir,qvm,qvr,qvi}$	shares parameters in CES function for investment goods
$\delta_{i,h}^{E,co,cl}$	shares parameters in CES function for households consumption
$\delta_{i,h}^{hr,hm}$	shares parameters in CES function for households consumption
$\delta_i^{gr,gm}$	shares parameters in CES function for government consumption

$\gamma_{i,j}^{vv,vir}$	shift parameter in CES functions for intermediate goods
γ_i^f	shift parameter in CES function for households consumption goods
γ_i^g	shift parameter in CES function for government consumption

$btax_i$	rate of business tax
$KM_{i,j}$	physical capital matrix
mps	rate of saving in institutions *dngins*
τ	rate of income tax
ρ	pure rate of consumer time preference
bb	rate of distortion or incentive to investment
δ	rate of depreciation
γ	efficiency parameter in household consumption