University of Strathclyde
Department of Economics

Evaluating the impact of pro environmental energy policy in Scotland and the UK: the case of increased efficiency in household energy use

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Gioele Figus

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Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: Date:

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Abstract

In this thesis, I use multi-sectoral computable general equilibrium techniques to investigate the system wide impacts of improvements in households' energy efficiency use, and technical progress in delivering households' energy services, in Scotland and the UK. The thesis consists of three main, self-contained but correlated essays.

The first essay looks the system wide impacts of an illustrative 5% energy efficiency improvement in households' energy use in Scotland and highlights the economic implications of increasing energy efficiency in a regional economy. I find that this results in a small economic stimulus, accompanied by a reduction in energy use that is less than the expected energy savings from the pure energy efficiency increase- the rebound effect. The stimulus is higher when migration of workers is allowed between Scotland and the rest of the UK. However, the higher expansion also delivers a higher rebound in energy use. The stimulus from the higher efficiency in energy use if further enhanced when I consider the impact of greater fiscal autonomy in Scotland, and allow for endogenous government expenditure or tax rates.

The second essay analyses the distributional impacts of households' energy efficiency improvements in the UK, focussing the attention on efficiency improvements in lower income households. I discuss whether there is an argument for the Government to fund household energy efficiency programmes via a temporary reallocation of current government expenditure or an increase in the income tax rate. While reallocating public spending has short-term negative impacts on demand over the period of the payment, the efficiency improvement delivers a net long-run stimu-

lus. However, an increase in income tax adversely affects the real take home wage and delivers a long-term reduction in GDP. In all scenarios, lower income households are able to increase their energy consumption and their income by approximately the same amount.

The third essay looks at the consumption of energy intensive services using the example of private transport. Here I argue that private transport should be modelled as a household self-produced commodity, composed of refined fuels and motor vehicles. By using a simple partial equilibrium model, I show that technical improvement in motor vehicles can reduce refined fuels use, when there is enough substitutability between the two inputs, and depending on the price elasticity of demand for private transport. By taking the case of the UK, and using a CGE model, I find that technical progress in motor vehicles delivers a small expansionary improvement if the consumer price index is adjusted to account for the implicit price of private transport.

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Chapter 1

An introduction and guide to the thesis

1.1 Context: a paradigm shift in analysing the impacts of energy efficiency

In this thesis, I focus on the economy-wide implications (including energy use) of efficiency improvements in households' energy consumption using the UK and Scotland as case studies. The UK and the Scottish Governments, albeit with different strategies, are both committed to delivering reductions in final energy demand through a range of policies, including energy efficiency improvements in industrial and household energy use. The UK Department of Business and Industrial Strategy (DBEIS) has recently renewed its commitment to "support greater energy efficiency" in the development of the new industrial strategy (DBEIS, 2017, p. 20). The Scottish Government (2017b) has recently released its new draft Energy Strategy, where it renews its commitment to pursue the Scottish Energy Efficiency programme (SEEP) (The Scottish Government, 2017a) as it "highlights a renewed emphasis on energy efficiency as a strategic priority [...], recognises significant economic benefits of energy efficiency investment and the importance of tackling fuel poverty" (The Scottish Government, 2017b, p. 11).

However, in this context, both Governments are constrained by a wider set of policy objectives and targets in terms of both wider energy strategies as well as a range of social and economic policies, while functioning in an environment of public sector budget constraints. These include, for example, delivering affordable energy for both industry and households (where fuel poverty is a key concern with regard to the latter) and sustainable and inclusive economic development.

Among other energy policy instruments, improving energy efficiency has received considerable attention both from the policy community and from academic researchers. The basic idea of energy efficiency is that physical energy sources such as oil, gas and coal can be used in a more productive way as a result of technical progress. This implies, for example, that households can achieve the same level of comfort from home heating, using less physical energy, less resources and generating a lower level of emissions.

The traditional approach in the energy economics literature has often focused on the energy reduction aims of energy efficiency actions and the induced 'rebound effect', which, in the simplest case, focusses on the fact that potential energy savings from efficiency increases can be partially offset by the initial relative price reduction of services delivered via the use of energy.[1] Although this has proven to be a concrete issue in several countries, an overly narrow focus on energy rebound has limited the scope of most analyses of energy efficiency to its capacity to reduce energy consumption, neglecting other important impacts, thereby potentially discouraging governments from pursuing energy efficiency enhancing policies.

The International Energy Agency (IEA, 2014) identifies the 'multiple benefits' of energy efficiency improvements, where energy use reduction is only one of many benefits that are likely to result from energy efficiency actions. From an economic perspective, the reduction in the relative price of using energy associated with energy efficiency improvements can have

[1] In Chapter 3 I describe different types of rebound effects and highlight the differences.

impacts that go beyond reduced energy use. For example, in production, where energy is an input, an improvement in energy efficiency will lower the cost of producing output and thus generate competitiveness effects similar to those delivered by technological progress in the use of capital or labour. However, even in consumption, the reduction in the relative price of delivering energy services (e.g. heating, lighting, driving a given distance) could free up resources that can be re-allocated to the consumption of other non-energy goods, thereby both boosting real income and stimulating aggregate demand. In turn, this may impact on investment, employment and overall disposable income (although, like any demand-driven expansion, it may also have negative impacts on competitiveness).

The IAE multiple benefits argument can be seen as a cornerstone for a paradigm shift[2] in the economic analysis of energy efficiency improvements. It shifts focus from the narrow perspective of a cost effective means of delivering a pure energy reduction to a more holistic analysis of how a wide range of economic and social benefits may be delivered. Even from a policy perspective, there is increasing interest in adopting a multiple benefit approach from governments around the world, because of the opportunity to achieve a higher coordination of multiple objectives, and to appeal to both political and public opinion by highlighting positive aspects of a more efficient use of resources. Again, for example the UK DBEIS in the new energy strategy aims to "secure the economic benefit of the transition to a low-carbon and resource-efficient economy"(DBEIS, 2017, p. 20)), while the Scottish Government defines "energy efficiency

[2]The shift mostly concerns the way policy thinks about energy efficiency issues. From a methodological point of view, the traditional framework already captures potential benefits, and trade-offs between different policy objectives.

as a strategic priority [...] recognising the significant economic benefits of energy efficiency investment" (The Scottish Government, 2017b, p. 10).

1.2 Household energy efficiency increases and potential benefits

In economics, energy efficiency is conventionally defined as any technical progress that allows an increase in the output per unit of physical energy. As I have already mentioned, in the use of energy in production, this is not very different from a technical improvement in capital use or an increase in labour productivity (although the analysis is complicated by the fact that energy is a produced input rather than a primary one). It is, therefore, an almost unambiguous outcome that improving energy efficiency in production would deliver a productivity-led stimulus and in most cases help to reduce energy use to some extent. There is an increasingly large literature using multi-sector, economy-wide computable general equilibrium (CGE) models to analyse the nature and outcomes of such a stimulus (see for example Allan et al., 2007; Broberg et al., 2015; Grepperud and Rasmussen, 2004; Hanley et al., 2009; Jenkins et al., 2011; Mahmood and Marpaung, 2014; Turner, 2009; Xiao et al., 2017; Yu et al., 2015).

However, with a change in demand from improved household's energy efficiency the outcome may be more ambiguous, and depends on a number of factors and economic conditions. Normally, the household budget is not fixed, and it will vary according to income from employment and other sources. A change in the composition of demand implies that some industries would sell/produce more and some other less. If, for example, non-energy consumption increases and energy consumption decreases, this would have gross impacts on the jobs and capital revenues involved in the supply chain of these goods. Thus, a net stimulus would be possible only if the lost income from the decreased production of energy is more than compensated by the increase in income from the higher production of non-energy goods. This type of issue could apply to some extent to energy efficiency improvements in industrial energy use. However, in the industrial energy use case, potential negative impacts are normally offset by competitiveness gains from reduced prices, at least in the case of a small open economy, such as Scotland and the UK. In contrast, in the household case if any supply constraint is imposed in production, such as a fixed labour force, the price of domestically produced goods will increase, as wages increase in response of any demand stimulus. This in turn impacts negatively international competitiveness and reduce exports demand. Clearly, these (and other) issues are of primary importance for any Government seeking to implement energy efficiency improvement with the double objective of reducing energy use without sacrificing economic growth.

However, the multiple benefits framework is not limited to macroeconomic gains. Energy efficiency improvements can be targeted to those households who are normally under-heating or 'under-powering' their homes and/or are considered to be fuel poor. Given that energy efficiency reduces the effective cost of energy, its introduction means that home heating and lighting become more affordable. Thus, governments could be persuaded to adopt these measures because of their commitment to social policies generally, and to energy affordability, inclusive growth and fuel poverty reduction in particular.

Overall, it is increasingly important in a policy context that the entire range of economic (and ideally social) impacts triggered by increasing household energy efficiency improvements must be clearly articulated. This thesis considers how a multi-sectoral system wide approach is required when trying to capture these multiple impacts simultaneously. The objective of this work is to develop modelling frameworks that can capture the complex interaction of these impacts and to use these to assess the capacity of energy efficiency improvements to make contributions to our understanding of the new paradigm of energy efficiency analyses.

1.3 CGE modelling

While many studies have used *partial equilibrium* models to estimate the impact of households' energy efficiency improvements, here I argue that, given the important links between the economy, energy use and environmental impacts, it is necessary to utilise a modelling framework that is capable, at least in principle, of capturing system wide interactions between energy/environmental issues and the economy. Moreover, given policy attention on multiple objectives for and outcomes of any type of policy, I consider that *computable general equilibrium* (CGE) analysis is particularly well suited to explore all the system-wide impacts of household energy efficiency improvements at regional or national level, here focussing on case studies for the UK and Scotland.

CGE models are widely used for the analysis of energy, environmental and economic policies, trade and fiscal issues, not only by the academic community but also by policy analysts and governmental bodies. For instance, the Scottish Government and HMRC use their own CGE models for policy analysis (The Scottish Government, 2014; HMRC, 2013), but also other countries such as Norway, US, Australia and institutions such as the European Commission and the OECD make extensive use of this modelling approach (Château and Lanzi, 2014; Holmøy, 2016; Mercenier et al., 2016; Pezzey and Lambie, 2001; The World Bank, 2011).

There are several reasons why CGE analysis more generally, and the specific model used in this thesis, is an appropriate modelling framework to adopt when exploring the multidimensional impacts of households' energy efficiency improvements, and analysing potential trade-offs and multiple benefits of energy efficiency. First, while most partial equilibrium models have only one economic sector, CGE models have an intrinsic **multi-sectoral** structure capable of capturing the economic response of different industries to an external disturbance, and how these responses may interact with one another. For example, if improvements in energy efficiency actually deliver a reduction in final energy use, this will result in a decreased demand for energy from households, which impacts energy producers and suppliers, their returns to capital and, thus, their investment decisions going forward. However, income effects from the reduced energy bill lead to increases in expenditure on other energy and non-energy goods, thereby positively impacting capital returns and investment decisions in those sectors, but also potentially increases embodied energy use in their supply chain. The overall impact on energy use would vary depending on the energy intensity of each sector that is positively or negatively impacted by the demand shift, and on the type of energy used. Thus, a knowledge of sectoral composition of any expansion is essential.

Moreover, in a CGE framework, where data permit, economic sectors can be easily disaggregated (or aggregated) to display more (or less) details about a specific industry's sales and purchases, and about the nature of each industry's final demand. For example, in Chapter 4, I propose a model that includes consideration of the UK household sector disaggregated by income quintiles. This facilitates analysis of the distributional impacts of energy efficiency, across groups that have different consumption patterns.

Second, CGE models capture **endogenous market prices and nominal incomes**. Energy efficiency is likely to trigger price responses when the economy adjusts to a new macroeconomic equilibrium after a disturbance. For example, energy firms may try to recover from revenue losses and reduced returns to capital when energy demand decreases by raising prices (Turner, 2009). These price decisions will affect intermediate and final consumption of energy across the economy. Moreover, as supply conditions and behaviour are endogenous to the model, expansions or contractions in the economy are reflected in income variations that impact household consumption decisions. This is perhaps one of the main advantages of CGE models, as prices and income variations can be of great importance when trying to assess household consumption decisions.

Third, it is possible in a CGE model to have an **endogenous government** sector. This implies that we can directly address government fiscal policies, linked to the actual implementation of energy efficiency, such as funding efficiency via taxation or changes in public expenditure composition. Moreover, for the particular case of Scotland, it allows us to run specific scenarios reflecting the new devolved fiscal powers that Westminster is giving to the Scottish Government (Scotland Act, 2016).

Fourth, depending on the configuration and specification of a CGE model, the **labour market** can be modelled as endogenous and with quite a high level of detail. The main area of focus is often to treat the real wage and employment as being determined within the CGE model. The Scottish model that I use in this thesis also offers the possibility of capturing interregional net migration of workers from Scotland to the rest of UK and vice versa. This is crucial to assess the impact of a policy in terms of job creation or destruction and on the purchasing power of households.

Fifth, CGE models increasingly involve **endogenous investment**. In the models used in this thesis, supply responses to any disturbance are determined in part by adjustment in capital stocks driven by cost minimising production technology. For example, if energy demand decreases, profitability falls, and energy firms will reduce their capacity and their capital stock. However, this happens gradually, according to different adjustment mechanisms.

Sixth, increasingly CGE models solve over **multiple periods and are dynamic**. The model that I adopt and develop for this thesis produces results for transition periods towards equilibrium. This can be particularly interesting for Governments who operate in a time-constrained framework governed by elections and other shorter term deadlines. Moreover, the model considers the dynamic choices of consumers and investors that can be either myopic or forward looking with perfect foresight. It is also possible to consider heterogeneous behaviour of firms and households, where one is myopic and the other is forward looking, and heterogeneity of behaviour within different groups of consumers.

Seventh, CGE models are increasingly developed to have **policy applicability and impact**. Because CGE methods are used by both the UK and Scottish Governments, I believe that, as well as producing useful results, my work can help to inform and address these Governments' use of CGE models. This can occur through stimulating a critical debate around CGE modelling for policy analysis, including implementation and applications, and through developing the knowledge for building more sophisticated models.

Of course, I acknowledge that CGE models have limitations that should be taken into account in their application. In fact, one of the objectives of this thesis is to address some of this limitations and try to move towards more robust modelling foundations. However, with this in mind, and for the reasons explored earlier in the text, I am convinced that CGE is the most appropriate modelling framework to use in the context of investigating and understanding the economy-wide impacts of increased household energy efficiency from the perspective of multiple policy objectives and outcomes.

1.4 Structure of the thesis

The remainder of the thesis is organised as follows. In Chapter 2 I provide an introduction to the CGE models of the UK and Scotland used in this thesis. My modelling work builds upon the existing CGE modelling framework developed by researchers of the Fraser of Allander Institute and Centre for Energy Policy at the University of Strathclyde. I describe the main components and features of the model, and highlight, when appropriate, the extensions to the model that constitute the originality of this work in terms of modelling. I report the full mathematical representation of the models in Appendix A. Although this does not directly constitute an output of the thesis, here I report that part of this thesis work is also the development of my own GAMS[3] codes, in order to be able to solve the simulation models for each chapter.

Chapter 3, 4 and 5 are three independent (but related) essays on the wider economic impacts of household energy efficiency improvements. Each paper aims to contribute to the academic literature, by discussing the implications of household energy efficiency enhancing policies in Scotland and the UK and testing the current techniques utilised for the analysis of economy-wide impacts of energy efficiency. However, I aim also to contribute to the current energy policy and economic debate of Scotland and the UK as a whole: the analysis are all policy relevant.

The first paper, corresponding to Chapter 3, is entitled '*Increasing energy efficiency in Scottish households: trading-off benefits of an economic stimulus and energy rebound effects?*'. This paper has a regional focus, and is dedicated entirely to the case of Scotland. In this work I start from the most recent analysis of economy-wide implications of improving households' energy efficiency in the UK (Lecca et al., 2014a) and extend it to study the implications of moving from the national case of the UK,

[3]General Algebraic Modelling System (GAMS) is high level mathematical command-line based system used to solve large scale optimisation problems, such as those composing a CGE model.

to the regional case of Scotland. The paper analyses the impacts of an illustrative 5% energy efficiency improvement in household energy use in Scotland. It initially replicates the analysis conducted in Lecca et al. (2014a), and then introduces additional regional-specific elements in the model, notably by including migration of workers between Scotland and the rest of the UK.

In the UK case (Lecca et al., 2014a), an energy efficiency improvement in household energy use results in a small economic stimulus, accompanied by a reduction in energy use that is less than the expected energy savings from the pure energy efficiency increase. However, the economic benefits are limited by the fact that households increase their consumption of goods and services, putting upward pressure on domestic prices and crowding out exports. Regions are normally characterised by more open goods and labour markets, given their integration with the host national economy. In the case where workers can freely migrate between regions in response to variations in wages and unemployment rate, the prices of goods and services in the economy tend to remain constant in the long-run. This is because the net in-migration triggered by the economic stimulus from the higher efficiency puts downward pressure of wages and prices. In equilibrium, because migration responds to differences between the regional and the national real wage (and the national real wage is exogenous) prices go back to the baseline value and the initial level of exports is restored.

However, in this paper I consider also the implications of potential new fiscal powers attributed to the Scottish Government by Westminster. In a context where economic activity is growing, tax revenues increase, giving room for additional stimulus to the economy via additional government spending. Alternatively, the additional revenue could be used by the government to reduce taxes on income. This work is the first economy wide study on the impact of household energy efficiency in Scotland to date. It contributes to the still small literature on the system wide impact of energy efficiency and proposes efficiency as a tool for regional development.

The second paper, Chapter 4, entitled '*Making the case for supporting broad energy efficiency programmes: impacts on household incomes and other economic benefits*' is more policy focused. Here I take the case of the UK, and look at the distributional impacts of households' energy efficiency improvements across households from different socio-economic groups. I explore the implications of energy efficiency for the wider economy, but also focus the attention on those households whose use of energy is considered to be insufficient to properly heat and light their homes, the so called 'fuel poor'.

Using a CGE model of the UK, I begin by introducing a 10% permanent costless increase in residential energy efficiency. Then I explore different options for the government to fund energy efficiency and improve the energy conditions of the poorest households. I look at two main options. The first is a temporary reallocation of government spending, to fund a permanent increase in residential energy efficiency. Although a decrease in government expenditure would have potential negative impacts on demand over the period of the payment, it does not cause the kind of distortive effects typically associated with taxation. The temporary negative impact only lasts for the duration of the change in spending, and it is followed by the same positive stimulus observed in the costless case.

The second option that I explore is a temporary increase in the income tax rate, to simulate a redistribution from richer to poorer households. This has more negative impacts, because of the impact of income tax variations on salaries and wage bargaining. However, again the temporary nature of the policy can be justified in the light of a medium to long term return from the investment in energy efficiency. This paper tackles the criticism of CGE studies on energy efficiency improvements of only considering costless efficiency changes. It also proposes an endogenous mechanism by which the Government can support efficiency programs and analyses its impacts.

The third paper, Chapter 5, is entitled '*Can a reduction in fuel use result from an endogenous technical progress in motor vehicles? A partial and general equilibrium analysis*'. Here I tackle a potential issue with the way energy consumption is modelled, and look at alternative ways of decreasing energy demand via technical progress. Also I consider whether this technical progress can deliver both fuel use reduction and an economic stimulus. Up to this point, in the thesis, I assume that households consume physical energy such as petrol or electricity similarly to other non-energy goods. However, in reality people consume energy services that are the result of a combination of physical energy and some energy-using technology.

I develop a simple partial equilibrium model, where households self-produce private transport, by combining motor vehicles and refined fuels (petrol and diesel). In turn, private transport is consumed directly by households along with all other consumption goods. In this context, I show that a technical improvement in motor vehicles can reduce the use of refined fuels, when there is enough substitutability between the two inputs, and even if fuels efficiency has not changed. The output of miles travelled produced by households ultimately depends on the elasticity of demand for this service. Given that a technical progress in motor vehicles decreases the price of a mile travelled, if the household's demand is price-elastic they will simply travel more, therefore demanding more fuels and motor vehicles. If the household's demand is price-inelastic it will demand less private transport and both fuel and vehicle use will decrease.

Taking the case of the UK, I then incorporate the partial equilibrium model described above into a CGE model. Simulation results show consistent results with the partial equilibrium model in regard to the composition of household consumption. However, macroeconomic impacts vary depending on how the consumer price index is calculated, in particular whether or not it includes the price of energy services self-produced by households.

This paper proposes a more sophisticated way of modelling energy services through the example of private transport, and to think of technical progress that is not directly energy saving as a potential endogenous mechanism for energy reduction in consumption. The paper also assesses through simulations the impact of vehicles efficiency improvements in the provision of the energy service private transport, and identifies the conditions under which this leads to fuels use reduction. Moreover, it assesses the impact of such efficiency improvements on the wider economy. It constitutes the basis for future development of micro-foundations of household energy consumption both in a partial and in a general equilibrium setting, and reflects on the importance of considering energy consumption in the context of its use and not as a simple consumption good.

In the final Chapter I draw the thesis' conclusions and general lessons, and I outline future plans for research and potential extensions to this work. The thesis contributes to the energy efficiency/economics literature in several ways. Firstly, the three core Chapters (3,4 and 5) tackle the energy efficiency literature under different perspectives, contributing to different literatures. The first paper has a regional focus. The main contribution of this work is in the system wide analysis of household energy efficiency improvements in Scotland. To the best of my knowledge, this is the first Scottish-focussed study in this field. It adds to the current debate in regional economics by proposing energy efficiency as a means not only to reduce energy use but also to promote regional development. Furthermore, it is also original in the analysis of energy efficiency improvements in the context of a fiscally devolved Scotland.

The second paper is more policy oriented. It extends previous work on system wide energy efficiency improvements in the UK households conducted by Lecca et al. (2014a) but adding depth to the analysis in at least two main ways. First, it considers the distributional impacts of energy efficiency improvements across different household income groups. While to the best of my knowledge, only one study to date considers the distributional effect of energy efficiency in the UK (Chitnis et al., 2014), this work is limited to the calculation of direct and indirect rebound effects and does not take into account economy wide impacts. Moreover, while past system wide studies have assumed costless energy efficiency improvements, I consider in this work the impact of energy efficiency measures funded via government spending and taxes on income. Simulation results show that, depending on the source of funding for the efficiency improvement and on the duration of the payments, costly energy efficiency improvements can have different short term implications, while in the long-run they tend to converge to the same equilibrium.

The third paper has a theoretical and analytical orientation. Here I consider ways of improving the modelling of energy intensive services using the example of private transport, adding to the micro literature that has started to consider such services as being composed of energy and some technology. However, while past studies have assumed that the role of technology is only to transform physical energy into service output (such as miles travelled for example), I argue that a technology/capital good such as motor vehicles can influence the price of the produced energy services, for example when its efficiency improves, affecting thereby the consumption of physical energy. Finally, in contrast to previous studies, this paper also assesses the system wide implications of efficiency improvements in motor vehicles, and the ability of such improvements to reduce fuel use and deliver an economic stimulus.

Finally, I conclude that the current work can be extended in several aspects. Among these, one natural extension is to model interactions of Scotland and Rest of UK (RUK) in a multiregional CGE modelling framework. This allows the capture of feedback and spillover effects between the two regions, and the impact of asymmetric policies as Scotland moves in the context of a more devolved fiscal system. Another natural extension is to explore other modelling techniques such as energy system models, which are currently used by both the Scottish and the UK Governments. From the technical modelling perspective, my main priority could be to test the implications of alternative micro foundations for example from behavioural economics models, both from the consumption and the production sides.

Chapter 2

An introduction to the AMOS-ENVI and UK-ENVI CGE models

2.1 Introduction

In economics, models are used to study specific real world issues in isolation. Over the years, a variety of models have been developed to explain specific aspects of economic systems such as consumption, production or labour market behaviour. Computable General Equilibrium (CGE) models take the complexity of economic systems whose components are believed to be well understood in isolation, but whose interaction is difficult to assess following a disturbance. Such interaction, is studied in CGE models by identifying the sign of each component's variation, as well as the magnitude of the variation. In doing this, CGE models analyse the countervailing forces operating within the economy as each market reacts to a disturbance and adjusts towards a new equilibrium. Essentially, CGE models provide a means of isolating the system-wide ramifications of any disturbance or intervention, including policy actions.

CGE models are widely applied by academics and practitioners to assess the economic impact of different disturbances. There are several reason for this. Firstly, CGE models are based on rigorous theoretical foundations. All CGE models are based on the general equilibrium theory of the existence of equilibria that clear supply and demand in all markets simultaneously (Arrow and Debreu, 1954). However, each component of a CGE model, consumption, investment, production etc., is also based on specific microfoundations. Secondly, CGE models are extremely flexible. Depending on the research question or policy issue to be analysed, different parts of a CGE model can be developed in more details, in order to provide a more accurate answer to a given question. However, at the same time, other elements can remain relatively simple and this allows us to keep track of results and avoid that the model becomes a 'black box'. Finally, CGE models are calibrated on real world data. These data can be disaggregated according to the specific issue to be addressed.

To develop a CGE model it is typically necessary to go through the following steps: specification, parametrisation, solution and ultimately simulation. The specification of a CGE model implies the development of theoretical structure represented by a set of equations describing a given general equilibrium model. The specification varies from model to model, and can be adapted according to the characteristics of the modelled economic system and of the needs of the researcher.

Once the theoretical structure has been decided, it is necessary to parametrise the model using data from the real world. Structural parameters are typically derived using a Social Accounting Matrix (SAM). However, depending on the structural form of the theoretical specification, other 'key' parameters, such as elasticities, are imposed exogenously to reflect for example the result of econometric analyses. All the remaining parameters are derived through the calibration process.

When these steps have been completed a CGE model is solved numerically, utilising different specialised software packages and algorithms such as GAMS. Essentially, the solution is found for a set of prices that satisfy the market clearing conditions of each market within the economy simultaneously, for given demand and supply functions. In the absence of any disturbance, the solution of the model simply replicates the benchmark values that have been used to parametrise the model. Policy impacts are evaluated by introducing a counterfactual (what if..?) simulation scenario and comparing the results with the business as usual scenario.

As flexibility is one of the strengths of CGE models, there is a wide variety of such models. Differences are normally determined in the theoretical specification and in the temporal and spatial dimension of the model. From the theoretical perspective, early CGE models were largely based on neoclassical assumptions of perfectly competitive markets (Shoven and Whalley, 1984). However, currently many models include elements of imperfect competition, and other market imperfections. For example, the models that I use in this thesis consider imperfectly competitive behaviour in the labour market.[1] Moreover, models can in principle include elements of behavioural economics, as well as other alternative theories. For the time dimension, simpler models assume fixed factors of production and are comparative static in nature. Other models include factors of production adjustment mechanisms of several types, and can be used to analyse the evolution of impacts across time, as well as across different equilibria (Pereira and Shoven, 1988). As I explain in Sections 2.2 and 2.4, the Scottish and the UK models adopted in this thesis allow different dynamic behaviour of households' consumption and firms' investment.

From the spatial perspective, CGE models can represent cities, regional, national or international economies, with the possibility of modelling multiple regions at the same time to study the interaction among these (Wiedmann, 2009). However, often, due to computational limits, models describing very large agglomerates of regions[2] are limited in other aspects, such as the specification of dynamic behaviour.

[1] I am currently working on developing monopolistic and imperfect competitive behaviour in the electricity market of the UK with colleagues of the Centre for Energy Policy, University of Strathclyde, as part of an EPSRC funded project.

[2] See for example the European Commission CGE model, RHOMOLO (Mercenier et al., 2016).

In the analysis of energy-environmental issues, CGE models have been widely adopted for at least two additional main reasons. First, most CGE models are based on sectoral data which offers details about the composition of energy production, industrial use of energy, and final demand. Energy use and emissions vary significantly among sectors, so that the composition of economic activities becomes critical. Second, because they have endogenous market prices and income. This is important especially in the determination of interconnections between energy/environment and the wider economic system (Bergman, 2005; Sue Wing, 2009).

In this dissertation I use two main CGE modelling environments called AMOS-ENVI and UK-ENVI. AMOS is the acronym of *A Model of Scotland*. This CGE model has been developed and maintained over the years at the University of Strathclyde starting from Harrigan et al. (1991). The ENVI extension of AMOS is specifically designed to analyse the impact of energy and environmental disturbances in the Scottish Economy (Allan et al., 2014; Hanley et al., 2009). UK-ENVI is a national version of AMOS-ENVI (Allan et al., 2007; Lecca et al., 2014a; Turner, 2009).

The two models have a similar structure, but they are calibrated on different datasets, and allow the choice of different macroeconomic closures appropriate to either a regional or a national economic system. In this chapter I outline the core common structure of the specification of the two models and highlight differences between the regional and the national models. The full mathematical representation of the models is provided in Appendix A.

AMOS/UK-ENVI are multisectoral, dynamic CGE modelling frameworks that offer the possibility of making different assumptions regarding household consumption, investment behaviour, labour market and government decisions. In the remainder of this Chapter I illustrate in turn the key characteristics of the models' specification main components.[3] Specifically, in Section 2.2 I describe the consumption's specification of the model, focussing on both intertemporal and on within period consumption. In Section 2.3 I describe the production structure of the model. In Section 2.4 I discuss investment behaviour in the myopic and forward-looking specifications. In Sections 2.5 and 2.6 I describe respectively the available different labour market and government closures. In 2.7 I provide a brief overview of the structure of the SAM used in the model. Finally, in Section 2.8 I describe the solution's procedure.

2.2 Consumption

2.2.1 Intertemporal consumption: myopic vs forward-looking behaviour

The consumption component of the model describes the behaviour of a representative household that makes consumption decisions over time and at each period in time. The models offer the possibility of considering the intertemporal consumption behaviour of 'myopic' or 'forward looking', perfect foresight households.

Myopic intertemporal consumption decisions are based on the follow-

[3]The basic structure of the CGE model in its non-energy version is largely based on Lecca et al. (2013). Although this thesis is meant to be self-contained, the reader can also refer to this work for further discussion about the model's characteristics.

ing conventional consumption function:

$$C_t = Y_t - S_t - HTAX_t - CTAX_t \tag{2.1}$$

In (2.1) total consumption C is a equal to income Y minus savings S, income taxes $HTAX$ and direct taxes on consumption $CTAX$. t is a subscript for a period of time, which is considered to be one year, given that the underlying data are annual. Any changes in income, savings or taxes are therefore reflected in each year's consumption decision. Households' income includes capital income KY and labour income LY, plus any transfer from Government and other institutions.

$$KY_t = dsr_{k,h} \sum_{j=1}^{J} KD_{j,t} \cdot rk_{j,t} \tag{2.2}$$

$$LY_t = dsr_{l,h} \sum_{j=1}^{J} LD_{j,t} \cdot W_t \tag{2.3}$$

In (2.2), capital income is described as the sum across sectors of capital demand KD times rent of capital rk and where $dsr_{k,h}$ is the share of capital income that goes to households and it is calibrated from the SAM.[4] Similarly, in (2.3) labour income is given by the share of labour income that goes to households $dsr_{l,h}$ times the sum of labour demand LD across sectors times the wage w. Households' income also includes transfers from the government and other institutions.

The myopic specification lacks any expectations of future intertemporal consumption decisions (Devarajan and Go, 1998; Go, 1994; Lecca

[4]Capital and Labour income are distributed among domestic institutions, such as households, government and firms.

et al., 2013; Partridge and Rickman, 2010). To accommodate future expectations we have the possibility of assuming that households have perfect foresight forward looking behaviour. The forward looking consumption model describes the behaviour of a representative household who seeks to maximise utility across time, subject to a budget constraint.

$$U^t(c_t, \ldots, c_T) = \sum_{i=0}^{T-t} \left(\frac{1}{1+\rho}\right)^t \frac{C_t^{1-\sigma}-1}{1-\sigma} \tag{2.4}$$

$$\text{so that } \dot{W} = Y_t + rW_t - Pc_tC_t$$

In equation (2.4) U is the intertemporal utility function, c is consumption at each time period t, ρ is the time discount factor and σ is the constant elasticity of marginal utility. The budget constraint states that at each period in time the change in total wealth W is a function of income, plus returns on wealth, minus consumption times the price of consumption Pc.

Households' wealth is composed of financial wealth (FW) and non-financial wealth (NFW) so that the following identity holds:

$$W_t = NFW_t + FW_t \tag{2.5}$$

The non-financial wealth includes wealth from labour income. It accumulates as follows:

$$NFW_t(1+r) = NFW_{t+1} + YL_t + \sum_{ins} TRS_{ins,t} \tag{2.6}$$

Equation (2.6) indicates that the compound value of today's non-financial wealth is equal to tomorrow's wealth plus net labour income YL, plus transfer from other institutions ins, such as firms and government, TRS. The financial wealth accumulation can be expressed as follows:

$$FW_t(1+r) = FW_{t+1} + KY_t - S_t \tag{2.7}$$

Equation (2.7) states that current compounded wealth is equal to future period's financial wealth, plus net income from capital KY minus savings S. The saving rate is exogenous and can be expressed as a share of income.

$$S_t = mps \cdot Y_t \tag{2.8}$$

where mps is the marginal propensity to save and it is a parameter calibrated from the SAM, while Y is total income and it is equal in equilibrium to the discounted sum of financial wealth plus non-financial wealth. The solution of the utility maximisation intertemporal problem gives the Euler equation describing the optimal path of consumption across time.

$$\frac{C_t}{C_{t+1}} = \left[\frac{Pc_t \cdot (1+\rho)}{Pc_{t+1} \cdot (1+r)}\right]^{-\frac{1}{\sigma}} \tag{2.9}$$

According to (2.9) with fixed exogenous interest rate r[5] the present discounted value of future consumption depends on future consumption prices. The parameter σ can be interpreted as the elasticity of intertemporal substitution, measuring how easily household substitute current consumption for future consumption. This is set to 1.5 (Lecca et al.,

[5] I assume a fixed world interest rate equal to 0.04% (Lecca et al., 2013).

2014b).

In a steady state equilibrium, the present value of wealth is equal to the discounted sum of net income, which implies that the myopic and forward looking behaviour produces the same equilibrium results. However, the short-run equilibrium and the adjustment paths in response to any disturbance to the economy differ between the two models (Lecca et al., 2013).

In this thesis I assume forward looking consumption behaviour in Chapter 3, in order to ensure consistency with the analysis of the national case study of the UK conducted by Lecca et al. (2014a). In this way, differences in results are purely driven by the regional nature of Scotland, reflected in the different dataset and in the assumption of interregional migration of workers. In Chapter 4, I assume that households are myopic. It can be argued that there is some degree of myopia in households' consumption behaviour. Therefore, the assumption of intertemporal perfect foresight, household maximising behaviour can be regarded as a limiting case that may not be a good representation of real consumption behaviour. Additionally, the analysis in Chapter 4 is focussed on the lowest income households, whose ability to optimise their lifetime income is significantly circumscribed by their dependence on transfers from government and other types of transfers. Ideally, I could have assumed that some groups are myopic and some other are forward-looking or some other type of behaviour.[6] However, in the context of Chapter 4 this would have gone beyond the main objective of the paper which is to investigate the implications of energy efficiency on

[6] In fact, it is straightforward to set the model to reflect this type of assumption.

lower income households. Finally, in Chapter 5, I focus on long-run equilibrium results, and therefore I utilise for simplicity the myopic model given that the results are the same for this specific equilibrium solution.

2.2.2 Intra-temporal consumption

Regardless of the dynamic specification, the intertemporal component of the consumption function only determines how aggregate household consumption is allocated across different periods in time. However, one of the main characteristics of CGE models is the possibility to identify the demand for a range of different consumption goods that are the outputs of productive industries. Previous versions of AMOS and UK-ENVI CGE models assume that household's aggregate consumption is allocated among goods according to its initial share of consumption, using a Leontief type function (see for example Allan et al., 2007; Hanley et al., 2006; Turner, 2009). This implies that when total consumption varies (i.e. disposable income changes) the consumption of each single good changes by the same proportion. However, those studies were mostly interested in industrial energy use and for this reason they do not model in details households' consumption.

However, when the focus of a study is on household energy use, energy consumption needs to be treated more carefully. Depending on household's consumption preferences, the consumption of certain energy or non-energy goods may be more or less price elastic and some goods may be complements or substitute to other goods. For this reason Lecca et al. (2014a) extends the earlier version of the UK-ENVI CGE model by assuming that household can choose to consume energy or non-energy goods. To this end they allocate aggregate consumption using a constant elasticity of substitution (CES) function where energy and non-energy are treated as imperfect substitute.

In Chapter 3, I follow Lecca et al. (2014a) and assume that within each period consumption C_t is allocated between energy goods EC and non-energy goods NEC so that:

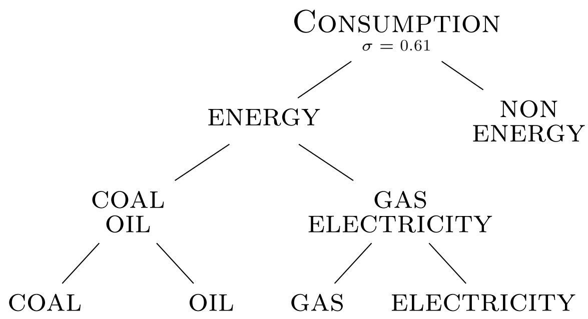
$$C_t = \gamma \left[\delta^E EC_t^{\frac{\varepsilon-1}{\varepsilon}} + (1-\delta^E) NEC_t^{\frac{\varepsilon-1}{\varepsilon}} \right]^{-\frac{\varepsilon}{\varepsilon-1}} \tag{2.10}$$

In (2.10) ε is the elasticity of substitution,[7] and measures the ease with which consumers can substitute energy goods for non-energy goods, $\delta \in (0,1)$ is the share parameter, and γ is an efficiency parameter. Any price change in one of these two goods will be reflected in some substitution towards the cheaper good. For example, if energy consumption becomes more efficient, its price in efficiency units (and possibly its market price) decreases, and the households will increase their demand for energy. However, if there is some complementarity between energy and non-energy, non energy consumption will also increase. The full list of equations describing household's intra-temporal consumption behaviour for this Chapter are reported in Appendix A.2.

The composite energy good EC in (2.10) includes the consumption of electricity, gas, coal and refined oil, as described in Figure 2.1. Although this is a straightforward way of allocating consumption between different energy goods, in the literature we find arguments in favour of alternative solutions. For instance, a growing (CGE and non-CGE) liter-

[7] Lecca et al. (2014a) also estimates the value of this elasticity over the short and the long-run. These are respectively 0.35 and 0.61

Figure 2.1: The structure of consumption in Chapter 3



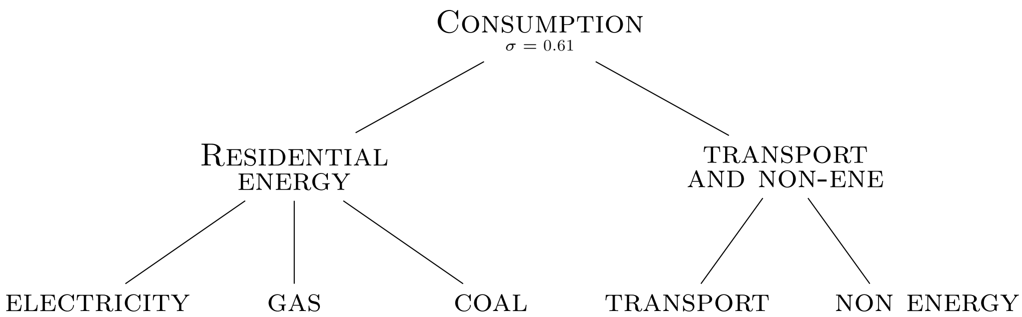
ature has introduced the distinction between static or non-motive energy and motive energy. Motive energy refers to the use of refined fuels in transport. Static/non-motive energy refers to residential energy use and other uses that are not intended for transport purposes (see for example Araar et al., 2011; Beuuséjour et al., 1995; Dissou, 2005; Fitzgerald et al., 2011; Gilchrist and Louis, 1995). While residential (static) energy use can be considered a primary need for households, because its under-consumption can rise health concerns particularly in very warm or hot climates, private transport (motive energy) use can be considered a non-essential service especially where public transport alternatives are available. For this reason, the two energy types require different policy attention.

In Chapter 4, I explore the distributional impact of households' energy efficiency improvements across different household income groups, accounting also for potential implications of increased energy efficiency on fuel poverty. While I do not directly model fuel poverty, I account for the fact that according to the most common definitions, fuel poverty refers to a situation where households are not able to properly heat or light their homes, that is they do not consume enough residential energy. This excludes the consumption of refined fuels for private transport. To represent this, I modify Equation (2.10) to exclude the consumption of energy for private transport from residential energy use. Additionally, to capture the distributional impacts I use a disaggregated dataset that reports household consumption data for five household income groups. Equation (2.10) is therefore modified as follows:

$$C_{h,t} = \left[\delta_h^E(\gamma RE_{t,h})^{\frac{\varepsilon_h - 1}{\varepsilon_h}} + (1-\delta_h^E)TNEC_{h,t}^{\frac{\varepsilon_h - 1}{\varepsilon_h}}\right]^{-\frac{\varepsilon_h}{\varepsilon_h - 1}} \tag{2.11}$$

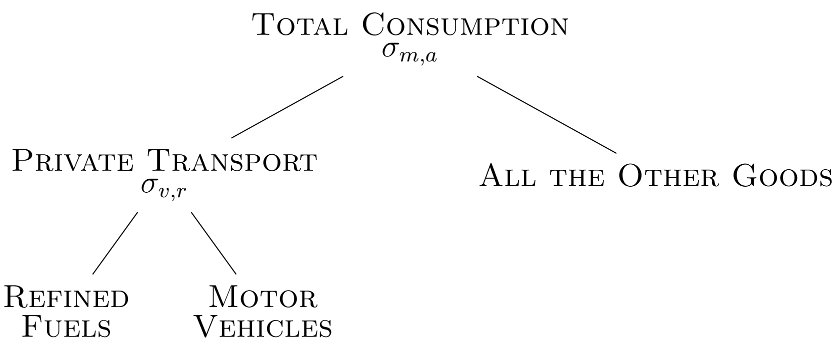
In (2.11) RE is residential energy consumption, that includes only electricity gas and coal, while $TNEC$ is non-energy consumption plus refined fuels consumption for private transport purposes. The subscript h indicates household group. This implies that each household has the same consumption structure, represented in Figure 2.2, but the underlying data are different. The full list of equations for this Chapter is reported in Appendix A.3.

Figure 2.2: The structure of consumption in Chapter 4



In Chapter 5, I start from the observation that households do not directly consume physical energy but they normally draw utility from services that are energy intensive, such as private transport, or space heating (Haas et al., 2008; Hunt and Ryan, 2015; Walker and Wirl, 1993). To reflect this, I explicitly model private transport as an example of an energy intensive service formed of refined fuels and motor vehicles. Given that there is no corresponding production sector for private transport, I assume that households self produce this service to consume it directly without selling it in a market (Barker et al., 2007), using vehicles and fuels for which there a is supply sector. This allows us to observe the implicit price of transport and to consider the price responsiveness of private transport consumption. To accommodate this modelling framework, I use a consumption structure similar to those in Bye et al. (2015), Schäfer and Jacoby (2005) or Steininger et al. (2007), represented in Figure 2.3.

Figure 2.3: The structure of consumption in Chapter 5



To implement this structure I modify Equation (2.10) as follows:

$$C_t = \left[\delta^{TR} TR_t^{\frac{\sigma_{m,a}-1}{\sigma_{m,a}}} + (1-\delta^{TR}) A_{h,t}^{\frac{\sigma_{m,a}-1}{\sigma_{m,a}}}\right]^{-\frac{\sigma_{m,a}}{\sigma_{m,a}-1}} \tag{2.12}$$

In (2.12) TR is private transport consumption, A is the consumption of all other goods, and $\sigma_{m,a}$ is the elasticity of substitution between private transport and all other goods. In turn, private transport is described by the following relation:

$$TR_t = \left[\delta^V(\gamma VC_t)^{\frac{\sigma_{v,r}-1}{\sigma_{v,r}}} + (1-\delta^V)F_t^{\frac{\sigma_{v,r}-1}{\sigma_{v,r}}}\right]^{-\frac{\sigma_{v,r}}{\sigma_{v,r}-1}} \quad (2.13)$$

where VC represents motor vehicles, F refined fuels and $\sigma_{v,r}$ is the elasticity of substitution between vehicles and fuels. In this case, the response to a change in efficiency (or other price change) is determined by a more complex system of relations as the two level nesting structure of the consumption function implies that there is a dual substitution between vehicles and fuels and between transport and everything else. The full list of equations for this part is reported in Appendix A.4.

Finally, all model versions (both AMOS and UK) assume that households consume both domestically produced and imported goods, where imported and domestic goods are imperfect substitutes (Armington, 1969).

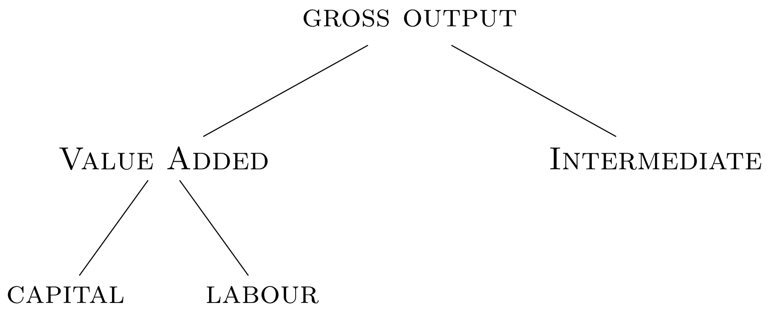
$$QH_{I=i,t} = \gamma_i^f \left[\delta^{hir} QHIR_t^{\rho_i^A} + (1-\delta^{hm})QHM_t^{\rho_i^A}\right]^{\frac{1}{\rho_i^A}} \quad (2.14)$$

In (2.14) QH is total household consumption by sectors, $QHIR$ is consumption of locally produced goods, and QHM is consumption of imported goods. With the price of imports being exogenous, substitution between imported and domestically produced goods depends on variations of national/regional prices.

2.3 Production

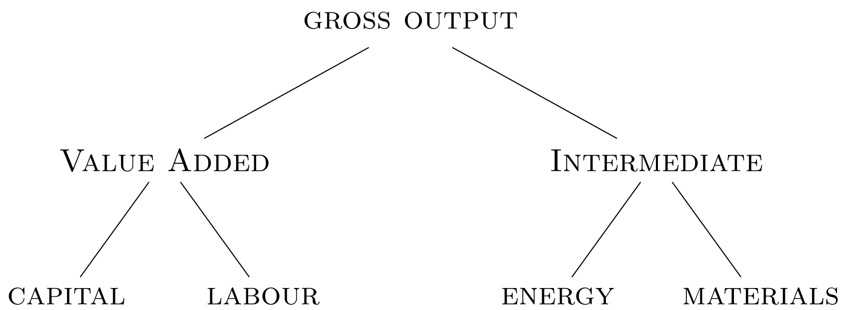
On the production side of the economy, the simple AMOS and UK CGE model assume that capital and labour are combined together to form value added. In turn value added combines with intermediates to produce gross output. This is described in Figure 2.4.

Figure 2.4: The structure of production in the non-energy AMOS and UK CGE models



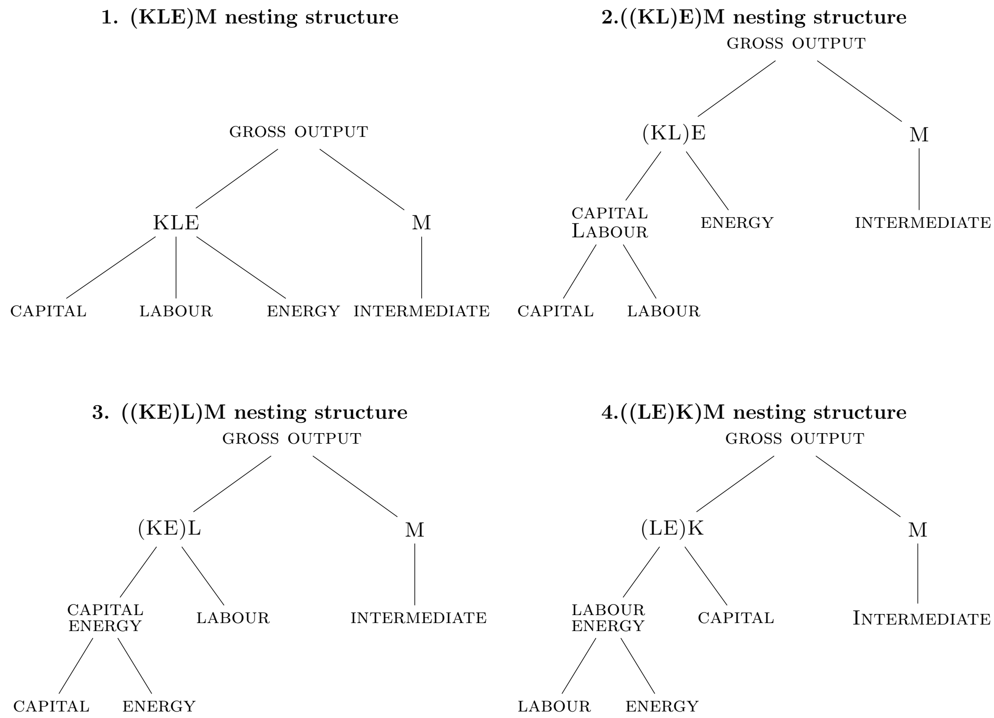
In the ENVI variant, energy is included in the production function as an intermediate input so that the structure described in Figure 2.4 becomes the one represented in Figure 2.5. This is the so called capital, labour, energy and materials (KLEM) production function.

Figure 2.5: The structure of production in AMOS and UK-ENVI models



In this model, energy is nested with materials to form intermediate inputs input because unlike capital and labour it is a produced input and an intermediate sector in the SAM. Although this is the most widely adopted production structure, in the literature we find examples of alternative nesting structures (see for example Grepperud and Rasmussen, 2004; Koesler and Schymura, 2015; Mahmood and Marpaung, 2014). There is an ongoing debate about whether energy should enter the production function, and whether it should be nested with materials, labour, capital or with both at the same time as illustrated in Figure 2.6 (Chang, 1994; Dissou, 2005; Kemfert, 1998; Koetse et al., 2008; Perroni and Rutherford, 1995; Van der Werf, 2008).

Figure 2.6: Main nesting structure combinations when energy is included in the production function



The implication of utilising different nesting structures in the nested CES production has also being discussed with experiments using AMOS-ENVI in Lecca et al. (2011). Currently, the research team of the University of Strathclyde with which I am working is estimating econometrically which structure best fits the current data, and what are the elasticity of substitution at each level. However, this is still a work in progress, and therefore for the purposes of the thesis, I adopt the classical KLEM structure in Figure 2.5, and I assume that this a CES function with a common elasticity of 0.3 (Harris, 1989; Lecca et al., 2014a). The full list of equations for this part of the CGE model is reported in Appendix A from (A.13) to (A.20).

Finally, to accommodate the use of intermediate products from the rest of the world (and from the rest of UK in the Scottish case) I assume that intermediate inputs are given as a combination of domestic and imported goods, and considered imperfectly substitutable (Armington, 1969) (see equation A.36), with an Armington elasticity of substitution of 2 (Gibson, 1990; Turner, 2009).

2.4 Investment

Similarly to consumption, investment can be myopic or forward looking. In the myopic case the time path of investment is given as follows:

$$I_{i,t} = v \cdot \left[K^{\star}_{i,t} - K_{i,t} \right] + \delta \cdot K_{i,t} \tag{2.15}$$

Equation (2.15) implies that at each time period investment is determined by the gap between the desired level of capital $K^{\star}_{i,t}$ and the actual level of capital $K_{i,t}$, plus the depreciation of the actual level of capital, and where v is an accelerator that measures the speed at which the capital stock adjusts to the desired level of capital (Jorgenson, 1963), and δ is depreciation rate of capital stock and it is equal to 0.1. The desired level of capital is determined by the cost minimising demand function for capital, given by the first order condition of the production function.

$$K^{\star}_{j,t} = \left(A^{x\rho_j^X} \delta_i^k \cdot \frac{PY_{j,t}}{uck_t} \right)^{\frac{1}{1-\rho_j^x}} \cdot Y_{i,t} \tag{2.16}$$

In Equation (2.16) A is a technology parameter, PY is the price of value added, uck is the user cost of capital, ρ is the elasticity of substitution between capital and labour, $\delta \in (0,1)$ is a share parameter, and Y represents value added. According to (2.16) the desired level of capital will respond to changes in the user cost of capital.

In steady state the following conditions are satisfied:

$$\begin{aligned} & K^{\star}_{i,t} = K_{i,t} \\ & \text{therefore} \\ & I_{i,t} = \delta \cdot K_{i,t} \end{aligned} \tag{2.17}$$

that is the desired level of capital $K^{\star}_{i,t}$ is equal to the actual level of capital $K_{i,t}$ and therefore capital supply is equal to capital demand. This implies that investment $I_{i,t}$ will only cover depreciation. In the thesis, I only use the myopic capital adjustment model in Chapter 5 where I focus on long-run equilibrium results and therefore the two models produce the same results (Lecca et al., 2013).

The forward looking investment option follows Hayashi (1982) and Abel and Blanchard (1983), and describes the choice of a representative agent seeking to maximise the value of firms V_t, subject to a capital accumulation function $\dot{K}_t$ constraint, so that:

$$\begin{gathered} \text{Max} V_t \sum_{t=0}^{\infty} \left(\tfrac{1}{1+r}\right)^t CF_t \\ \text{subject to } \dot{K}_t = I_t - \delta K_t \end{gathered} \tag{2.18}$$

In (2.18) the cash flow CF is given by gross profits less investment expenditure J which is defined as:

$$J_{i,t} = I_{i,t}\left(1 - bb - tk + \theta(x_t)\right)$$

$$\theta(x_t) = \left(\frac{\beta}{2}\right)\frac{(x_t - \alpha)^2}{x_t} \text{ and } x = \frac{I_t}{K_t} \tag{2.19}$$

where bb is the rate of current incentive to investment, tk is the marginal tax credit on investment. $\theta(x_t)$ is a quadratic adjustment cost function with parameters α and β and is increasing in the investment capital ratio (Devarajan and Go, 1998; Go, 1994; McKibbin and Wilcoxen, 1999). It implies that the firm does not instantaneously adjust to the desired level of capital but makes smaller stock adjustments over time. The solution of the problem gives the law of motion of the shadow price of capital, λ_t, and the tax adjusted Tobin's q time path of investment (Abel and Blanchard, 1983; Go, 1994; Hayashi, 1982).

$$\dot{\lambda}_{i,t} = \lambda_{i,t}(r_t + \delta) - R^k_{i,t}$$

$$\text{where } R^k_{i,t} = rk_t - Pk + (x_t)^2\theta'_t(x_t) \tag{2.20}$$

$$\frac{I_t}{K_t} = \alpha + \frac{1}{\beta}\cdot\left[\frac{\lambda_{i,t}}{Pk_t} - (1 - bb - tk)\right] \tag{2.21}$$

In Equation (2.21) the term in brackets represents the tax adjusted Tobin's q. With all the other terms fixed, investment responds to differences between the shadow price of capital λ, which indicated the market value of capital and hence the profitability to invest, and the price of capital goods Pk which represents the cost of replacing the capital stock. When the value of the firm and hence the shadow price of capital increases, Tobin's q is greater than 1 and investment will be positive. Similarly when λ decreases, the value of the firm is falling, and investment will reduce. However, because the steady state conditions are the same, myopic and forward looking investment produce identical long-run results, but they differ in terms of transition period adjustments.

2.5 The labour market, wage bargaining and migration

One of the main advantages of AMOS and UK ENVI models, is the possibility of making different assumptions regarding the labour market. In the current version, both models include three main labour market closures. These are wage bargaining, fixed real wage, and fixed nominal wage.

$$\text{wage setting} \begin{cases} ln\left[\frac{w_t}{cpi_t}\right] = \varphi - \epsilon ln(u_t) \text{ bargaining} \\ \frac{w_t}{cpi_t} = \frac{w_{t=0}}{cpi_{t=0}} \text{ fixed real wage} \\ w_t = w_{t=0} \text{ fixed nominal wage} \end{cases} \tag{2.22}$$

In the wage bargaining case, the real wage is determined in an imperfect competition setting, where the bargaining power of workers and hence the real consumption wage is negatively related to the rate of unemployment (Blanchflower and Oswald, 2009). In (2.22), $\dfrac{w_t}{cpi_t}$ is the real consumption wage, φ is a parameter calibrated to the steady state, ϵ is the elasticity of wage related to the level of unemployment u, and takes the value of 0.113 in AMOS and 0.068 in UK-ENVI (Layard et al., 1991).

The fixed real wage reflects the case where the worker's bargaining power ensures that the purchasing power remains constant over time, in a 'real wage resistance hypothesis'. The fixed nominal wage assumes that the wage is determined exogenously. This is a typical Keynesian closure. It is designed mostly for the Scottish model, to reflect the case where wage bargaining occurs at the UK level and the region takes the bargained wage exogenously (Harrigan et al., 1991).

The steady state condition for the labour market requires that the labour demand is equal to the labour supply minus the unemployment rate as follows:

$$LS_t \cdot (1 - UN_t) = E = \sum_{j=1}^{J} (LD_{j,t}) \tag{2.23}$$

In the UK-ENVI model, the working population is generally assumed to be fixed and exogenous. In AMOS-ENVI we model interregional migration from Scotland to the rest of UK as follows:

$$nim_t = \zeta - v^u \left[ln(u_t) - ln(\bar{u}^N) \right] + v^w \left[ln(w_t/cpi_t) - ln(\bar{w}^N/\overline{cpi}^N) \right] \tag{2.24}$$

In (2.24) net migration rate nim responds to the difference between regional and national real wage, and regional and national unemployment, subject so the elasticities v^u and v^w that measure the responsiveness of workers migration to the differentials (Layard et al., 1991), and where ζ is a parameter calibrated to the steady state.

2.6 Government

The Government collects revenue from taxes and spends it on a series of economic activities as follows:

$$GOVBAL_t = GY_t - GEXP_t \tag{2.25}$$

In Equation (2.25)[8] $GOVBAL$ is the government's budget, $GEXP$ is government expenditure and GY is government income. The identity in (2.25) allows alternative assumptions of government policy. In general, the Government can choose either to balance the budget or not. When we assume a balanced budget (GOVBAL fixed) the Government can either adjust its current consumption (GEXP) or adjust its income (GY) through varying the tax rate. On the other hand, when the Government fixes the expenditure, either tax rates or Government's budget become endogenous.

The traditional closure for the Scottish model implies that the government's expenditure is completely exogenous and the government's budget is endogenous. Thus, tax revenues accrue to the central Government in Westminster, to represent the so called 'Barnett' formula (Edmonds, 2001). However, with the gradual devolution of fiscal powers from the central Government of the UK to Scotland, this closure will become increasingly less accurate. Given that we are still in a transition period, in Chapter 3 I explore the key principles of allowing for a greater fiscal autonomy in Scotland by assuming that the Scottish Government maintains a fixed budged (GOVBAL), and either government expenditure or

[8]This is a compact version of Equation (A.40).

income tax rate are endogenous.

In the UK model however, releasing the government's budget has consequences on the public debt, and this has implications for the balance of payments. For this reason, I assume for simplicity a balanced budget constraint, with endogenous government expenditure and fixed tax rates. This implies that any changes in tax revenues will directly impact government current expenditure.

2.7 The Social Accounting Matrix

CGE models are typically calibrated on a social accounting matrix (SAM). In this thesis, the AMOS and the UK ENVI models are respectively calibrated on a 2009 Scottish SAM and a 2010 UK SAMs.[9] A SAM can be defined as a set of accounts of goods and services flows, incomes and factors of production for a given time period, which is typically one year, and for a given nation, region, or sets (or subsets) of regions. The SAMs used in this thesis are constructed as extensions to the Input Output (IO) accounts (Leontief, 1936, 1941), following the methodology described in Emonts-Holley and Ross (2014). For this reason I first provide a brief overview of what an IO account is, and then highlight the main differences between IO and SAM.

An IO table reports information about sales and purchases among intermediate industries, final demand and value added within a nation, region or other types of spatial agglomerates, and for a given period of

[9] The two datasets are published by the Fraser of Allander Institute, University of Strathclyde, and they can be downloaded at `http://www.strath.ac.uk/business/economics/fraserofallanderinstitute/research/economicmodelling/`.

time. A schematic representation of an IO table is reported in Figure 2.7. The main component of the IO is the 'interindustry transaction' matrix **T** where each industry is identified by the set j, for $j = (1, \ldots, J)$. **T** is JxJ matrix, where the rows describe the distribution of each industry output among other industries under the form of sales, while the columns describe the sectoral composition of the output, or purchases from other industries (Miller and Blair, 2009). This means that each industry appears both in the column as a buyer, and in the rows as a seller. Transactions are reported in each cell, typically in monetary terms at current prices.

The matrix **U** is a JxA final demand matrix, where a is the set of all institutions so that $a = (1, \ldots, A)$. This matrix reports the final demand of each sector from several domestic institutions such as government, households and capital formation, as well as foreign institutions, which is the external transactor and can include exports to other regions or purchases by non-resident households. Finally, the factors of production matrix, **Y**, is a BxJ matrix where b is the set of factors of productions and $b = (1, \ldots, B)$. This table reports information about inputs that are non-produced, such as income from employment and other value added, or inputs that are produced outside the economic system such as imports. A key characteristic of the IO table, is that total gross output equals total gross input. This means that the IO can already be regarded as a general equilibrium system.

IO tables are a useful tool to describe the productive structure of an economic system, and how income (GDP) is produced within the system. It also identifies the structure of demand of different institutions within

Figure 2.7: Schematic representation of IO accounts

			Sales →							
			Production			Final Demand				
			Industry 1	Industry 2	Industry J	Household	Government	Capital formation	External	
← Purchases	Production	Industry 1								Total output
		Industry 2		**T**			**U**			
		Industry J								
	Primary inputs	Labour								
		Other value added		**Y**						
		External								
				Total input						

Figure 2.8: Schematic representation of a SAM

			Sales →									
			Production			Factors		Final Demand				
			Industry 1	Industry 2	Industry J	Labour	Other VA	Household	Government	Corporate	Capital formation	External
← Purchases	Production	Industry 1										
		Industry 2		**T**						**U**		
		Industry J										
	Institutions	Household										
		Government					**X**			**W**		
		Corporate										
		External										
	Factors	Labour		**Y**								
		Other value added										

a given economy. However, the IO accounts do not describe how income is distributed among different institutions, and what are the transactions among institutions. For example, from the IO we know how much households buy from each sector. However, we do not know where the income for consumption comes from, how taxes are paid, how much subsidies are received, and if any income is saved.

For this reason, the SAM incorporates the IO accounts and extends them to include information about incomes flows, transfers between different institutions, savings and investment (Hosoe et al., 2010; Keuning and Ruijter, 1988; Stone, 1986). In this way, the SAM describes not only economic information about a given economy but also social information. The basic structure of the SAMs used in this thesis is described in Figure 2.8. By comparing Figure 2.7 and Figure 2.8 it is straightforward to identify the differences between the two accounting systems. The matrices **T**, **U** and **Y** are the same as in the IO. However, there are two additional matrices, **X** and **W**. **X** is an AxB matrix representing income payments from factors to institutions. It reports for example income from labour earns by households, or capital income from firms ownership transferred to households, government, corporate. **W** is an AxA matrix. It reports transfers among institutions. For instance, **W** includes payments to government under the form of taxes, subsidies and intra households or intra firms transfers.

Similarly to the IO accounting framework, a characteristic of the SAM is that total receipts are equal to total outlays. Again, this implies that the SAM is already a general equilibrium system and for this reason it constitutes the ideal starting point for the construction of a full CGE model. Another advantage of the SAM is that each account can be disaggregated to display higher level of details. For example, in Chapter 4, I use a version of the UK SAM where the household sector is disaggregated into 5 income quintiles. This means that instead of having one single household final demand column, as in Figure 2.8, we have 5 columns, one for each income group. Similarly, the household row that crosses the matrices **X** and **W** is divided in five rows, to display household income and transfer corresponding to each income quintile.

Both the Scottish and the UK SAM report information about 104 industries, which are derived from the full the Input-Output accounts (the interindustry matrix). To facilitate the solution of the CGE model, and the interpretation of the results, these industries are aggregated to a smaller number. This is a common procedure for the solution of CGE models, as well as for IO and SAM multiplier analysis. In the AMOS-ENVI model used in this thesis the sectors are aggregated to 21 (see Appendix B). In the UK-ENVI model used in Chapters 4 and 5 I aggregate the sectors to 30 industries (see Appendix C).

2.8 Solution procedure

The model is solved as a system of non-linear equations using the solver CONOPT3 in GAMS. I follow the common procedure of assuming that the economy is initially in steady state equilibrium (Adams and Higgs, 1990). I solve the model in the absence of disturbances, to verify that the benchmark database is exactly replicated. Following the introduction of a disturbance the model runs for a period of time sufficient to allow the economy to find a new steady state equilibrium. In the first period the capital stock and the working population (in the Scottish model) are assumed to be constant. This is to reflect the fact that capital stock and labour force adjustment are longer term processes. This period represent the short-run equilibrium solution. The long-run equilibrium solution is identified as a situation where capital stocks and the working population (again only in the Scottish model) are completely adjusted and the economy is in a new steady state equilibrium.

Chapter 3

Increased energy efficiency in Scottish households: trading-off benefits of an economic stimulus and energy rebound effects?

3.1 Introduction

In the analysis of energy efficiency improvements, the rebound argument has received a great deal of attention (Dimitropoulos, 2007; Jenkins et al., 2011; Sorrell, 2007; Turner, 2013; Van den Bergh, 2011). It focuses on the fact that the potential for energy-saving from technologies aimed at reducing energy consumption, can be partially, or even wholly, offset by increased energy demand from the consequent energy price reduction (Khazzoom, 1980, 1987) -the so-called rebound effect. For this reason, it has been generally considered that the boost to energy demand is an undesired consequence of energy efficiency policies (Gillingham et al., 2016), and one that needs to be taken into account when assessing the ability of such policies to reduce the demand for energy.

However, recent studies have noted that the energy rebound effect is linked to a wider range of positive economic benefits derived from higher energy efficiency (Barker et al., 2007, 2009; Gillingham et al., 2016; Turner, 2013). In a recent report, the International Energy Agency (IEA, 2014) argues that increasing energy efficiency could deliver significant social and economic benefits that go beyond the traditional single objective of reducing energy demand. From an economic perspective, energy efficiency has been shown to positively impact on key macroeconomic indicators, such as employment, exports, and total output (Allan et al., 2007; Barker et al., 2009; Turner, 2009, 2013).

Computable General Equilibrium (CGE) models have often been used to investigate the economy-wide impacts of energy efficiency improvements, including the 'rebound effect', because of their intrinsic multi sectoral structure and whole economy characteristics (Gillingham et al., 2016; Sorrell, 2007; Turner, 2013). Using CGE frameworks, studies focused on assessing rebound from energy efficiency increases in production have already underlined how a more efficient use of energy can deliver significant economic benefits. For example Broberg et al. (2015), Hanley et al. (2009), Turner (2009) and Yu et al. (2015) find that improving energy efficiency in production would lead to a productivity-led expansion. The findings are quite intuitive, as in these studies energy is one of the production inputs, along with capital, labour and materials. This means that improving energy efficiency will deliver similar types of effects as improving capital or labour efficiency, although with some differences, given that energy is used in smaller proportions and is a produced rather than a primary input.

However, macroeconomic impacts of energy efficiency have been also observed when energy efficiency increases in household consumption. For example Lecca et al. (2014a) show that a more efficient use of energy could lead to a reallocation of increased household expenditure towards non-energy sectors, thereby stimulating the economy through a shift in aggregate demand, but with some negative impacts on competitiveness and export demand.

The aim of this paper is to analyse the economy-wide impacts of increasing household energy efficiency in a regional context, accounting both for 'cost' of the rebound effect in energy use and for the potential benefits of energy efficiency. I use Scotland as case study, and compare my analysis to Lecca et al. (2014a), which focuses on the UK case. To this end, I use a regional Computable General Equilibrium (CGE) model of the Scottish economy.

Focusing on the case of Scotland allows me to highlight the implications of moving from a national to a regional context when analysing the system-wide impacts household energy efficiency improvements. There are countervailing effects: the greater openness of regional economies leaves them more sensitive to induced changes in competitiveness; but the greater supply-side responsiveness of regional economies acts to limit the scale of any such changes. Overall, I find that household energy efficiency can be an effective instrument of regional development policy, and that it does indeed typically generate a double (or multiple) dividend.[1]

The rest of the paper is organised as follows. In Section 3.2 I define the rebound effect and review the literature. In Section 3.3 I describe the CGE model used for this analysis. In Section 3.4 I illustrate the simulation Scenarios. In Section 3.5 and 3.6 I describe the results and discuss the main implications in the context of the conventional fiscal arrangements for Scotland under which the budget constraint of the devolved Government does not vary with economic activity. In Section 3.7 I explore the impact of increased household energy efficiency in the case in which the Scottish Government enjoys a much greater degree of autonomy, as under the new fiscal arrangements that are currently in the process of being implemented (Scotland Act, 2016). In Section 3.8 I conclude.

[1] The double dividend argument can be decomposed into a number of multiple benefits as intended by IEA (2014)

3.2 The rebound effect

3.2.1 Direct, indirect and economy-wide rebound effect

Improving energy efficiency, whether in its industrial use or in consumption has been often associated with the rebound effect (Khazzoom, 1987, 1988; Saunders, 2000).[2] In general terms, I define the rebound effect as being the ratio between the actual energy savings (AES) obtained from increasing energy efficiency, and the potential energy savings (PES),[3] so that:

$$R = \left[1 - \frac{\text{AES}}{\text{PES}}\right] \cdot 100 \tag{3.1}$$

Depending on the focus of the analysis we may decompose the rebound effect in order to distinguish between direct rebound, indirect rebound and economy-wide rebound. In the literature we find several ways of defining these three types of rebound, and also different taxonomies (see for example Gillingham et al., 2016; Greening et al., 2000; Sorrell, 2007; Turner, 2013). However, here I follow Lecca et al.'s (2014a) approach.

The direct rebound effect occurs when an increase in energy efficiency in a specific energy use, decreases the price of energy in efficiency units,

[2]The rebound effect has his roots in the pioneering work of Jevons (1865), who observed that increasing the efficiency of the use of coal in British industries in the 19^{th} century could actually lead to an increase in energy demand (the so called Jevons paradox). The rebound effect has then been extended to the household context by Khazzoom (1980, 1987).

[3]The potential energy savings correspond to the engineering effect of introducing a more efficient energy technology (i.e. a 5% more efficient heater). For a different approach to considering rebound in a general equilibrium setting see Guerra and Sancho (2010) who quantify the expected energy savings in an Input-Output modelling framework in terms of quantity adjustments in the energy supply chain.

leading to a rise in energy demand. For example following the installation of a new more efficient boiler, a household decides to heat its home for more hours per day or at a higher temperature, offsetting the expected engineering energy savings.

The indirect rebound effect may be defined in terms of re-spending of savings following a more efficient use of energy, under the assumption of fixed nominal income and prices (Lecca et al., 2014a). It could involve re-spending towards other energy services, for example using the savings from a more efficient heater to drive a car more, or cook more, or towards non-energy goods (clothing, leisure etc.) produced using energy. It focuses on considering the embodied use of energy in the supply chains of energy and non-energy goods.

Following Lecca et al. (2014a) I define the economy-wide rebound effect as including both direct and indirect rebound and also accounting for the wider set of economic impacts that occur as nominal income and prices adjust in response to the changing demand and supply, following the initial increase in energy efficiency.

3.2.2 Literature

Several contributions focus on energy efficiency and rebound effect from increased of household energy efficiency (Chitnis et al., 2014; Chitnis and Sorrell, 2015; Druckman et al., 2011; Frondel et al., 2012; Linn, 2013; Lin and Zeng, 2013; Schwarz and Taylor, 1995; West, 2004).[4] A key char-

[4]For extended literature reviews on the state of knowledge of rebound effect see Dimitropoulos (2007); Jenkins et al. (2011); Sorrell (2007); Turner (2013); Van den Bergh (2011)

acteristic of this literature is that the rebound effect is analysed mainly in a short-run context, it is limited to the micro level and focused on the direct rebound effect. This also means that most of the studies are based on partial equilibrium analysis, which is not able to capture the economy-wide effects of an improvement in energy efficiency, where incomes (in the household and other sectors) will be further impacted by supply side responses.

A number of studies investigate the rebound effect in an Input-Output (IO) setting (Chitnis et al., 2014; Chitnis and Sorrell, 2015; Druckman et al., 2011; Freire-González, 2011). Although the IO modelling framework may be considered a simple general equilibrium model, Lecca et al. (2014a) explain that rebound at this level cannot be considered as economy-wide rebound, because of the assumption of fixed nominal incomes and market prices.

In a CGE framework, a number of authors have examined the economy-wide impacts of increased energy efficiency on the production/industrial side of the economy (e.g. Broberg et al., 2015; Grepperud and Rasmussen, 2004; Glomsrd and Taoyuan, 2005; Koesler et al., 2016; Yu et al., 2015). Some studies have considered the case of UK and Scotland (see for instance Allan et al., 2007 and Turner, 2009 for the UK; Anson and Turner, 2009 and Hanley et al., 2009 for Scotland). However, all these contributors focus on efficiency improvements in production, and the economy-wide rebound effects (along with an expansionary impact on the economy) are driven by increased productivity and competitiveness.

To the best of my knowledge, few CGE studies focus on the economy-wide effects of increased household energy efficiency (Duarte et al., 2016;

Dufournaud et al., 1994; Koesler, 2013; Lecca et al., 2014a). Among the published works, Duarte et al. (2016) investigates different energy savings policies, including increased energy efficiency improvements in Spain. However, this study is quite specific to the Spanish economy characterised by very different energy needs, compared to Scotland, and focusses mostly on the effectiveness of energy saving policies on CO_2 emissions.

Lecca et al. (2014a) study the economic impact of an across-the-board 5% improvement in the energy efficiency of UK household. They illustrate the additional insights obtained in moving from partial to full general equilibrium analysis by calibrating models with different degrees of endogeneity on a common dataset. This is done by starting from an econometric analysis of rebound, then moving to an Input-Output framework, and eventually adopting a full general equilibrium model with endogenous prices and income. On this basis, they show how it is possible to obtain a decomposition of economy-wide rebound effects into areas that may merit differential policy responses.

In Lecca et al. (2014a), the general equilibrium analysis of energy efficiency is carried out in two stages. Firstly, the authors introduce an efficiency improvement to reflect an increase in the value of energy expressed in efficiency units, meaning that households can consume the original 'pre-efficiency' bundle of goods (energy and non-energy) but using less physical energy. This stimulates the wider economy through an increase in aggregate demand, because households would respond to the lower energy price (expressed in efficiency units) by substituting the consumption of energy goods for the consumption of non-energy goods.

However, while in studies focused on industrial energy use, such as Allan et al. (2007) and Turner (2009) the economic expansion is driven by an increase in competitiveness, in Lecca et al. (2014a) the demand-led growth puts upward pressure on consumption prices and so decreases competitiveness, partially crowding out exports.

Secondly, to understand how this loss in competitiveness may be avoided, Lecca et al. (2014a) hypothesise that the energy efficiency improvement in household energy use is reflected in an overall decrease in the cost of living. They model this by simply adjusting the consumer price index (*cpi*) so that it is calculated to include the price of energy goods expressed in efficiency units and the price of non-energy goods. Thus, when energy efficiency improves, the *cpi* decreases, increasing competitiveness and putting downward pressure on the nominal wage.

In this paper, I build on the general equilibrium analysis of Lecca et al. (2014a), but focus on a regional case study within the UK, using a single region CGE model of the Scottish economy. In order to emphasise the implications of moving from a national to a regional context, I initially replicate the type of analysis carried out in Lecca et al. (2014a).[5] Then, I extend this analysis by relaxing the assumption of a fixed working population imposed in Lecca et al. (2014a) to consider the impacts of interregional migration in response to differences in relative unemployment and wage rates. This provides another mechanism by which reduced competitiveness effects observed in the national case may be reduced. Finally, I explore the implications for this analysis of enhanced

[5]The key differences between the national model in Lecca et al. (2014a) and the regional model used in this Chapter are explained in Section 3.3.

fiscal autonomy in Scotland by exploring the consequences of assuming that the Scottish Government balances its own budget. This provides an additional source of stimulus where the economy is expanding since the additional tax revenues may be used either to increase regional public spending or reduce (devolved) tax rates.

3.3 The CGE model

To identify the general equilibrium impacts of energy efficiency I use the AMOS-ENVI[6] CGE model for Scotland. This model is based on the general AMOS CGE framework with forward-looking agents explained in Lecca et al. (2013) but extended to incorporate a more detailed structure of energy demand and supply (Lecca et al., 2014a).

The regional focus of AMOS-ENVI is reflected in three main characteristics. First it is calibrated using data for Scotland. Second, it does not impose the balance of payments constraint, to reflect the fact that regions do not possess a full range of fiscal and monetary policies, and receive transfers from the central Government.[7] Third, it allows for flow migration, to reflect the free circulation of workers within the UK territory.

[6] AMOS is the acronym of a micro-macro model of Scotland and it is the name of a CGE modelling framework developed at the Fraser of Allander Institute, of the University of Strathclyde. ENVI indicates a version of this model developed for the analysis of energy/environmental impacts of a range of policies and other disturbances.

[7] See Lecca et al. (2013) for a detailed discussion of this aspect.

3.3.1 Consumption

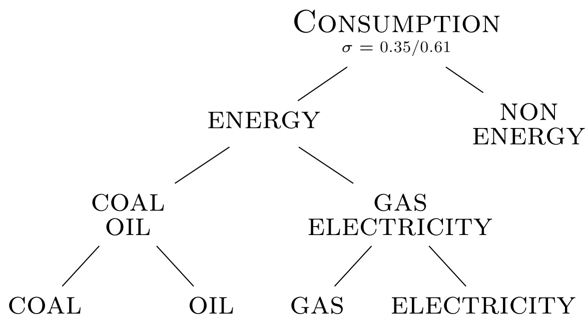
Consumption is modelled to reflect the behaviour of a representative household that maximises its discounted intertemporal utility, subject to a lifetime wealth constraint. The solution of the household optimisation problem gives the optimal time path for consumption of the bundle of goods C_t.

To capture information about household energy consumption, C_t is allocated within each period and between energy goods EC and non-energy goods NEC so that:

$$C_t = \left[\delta^E(\gamma EC_t)^{\frac{\varepsilon-1}{\varepsilon}} + (1-\delta^E)NEC_t^{\frac{\varepsilon-1}{\varepsilon}}\right]^{-\frac{\varepsilon}{\varepsilon-1}} \tag{3.2}$$

In (3.2) ε is the elasticity of substitution in consumption, and measures the ease with which consumers can substitute energy goods for non-energy goods, $\delta \in (0,1)$ is the share parameter, and γ is the efficiency parameter of energy consumption. The consumption of energy is then divided into two composite goods, coal and refined oil and, electricity and gas. These in turn split into the four energy uses, refined oil, coal, electricity and gas, through a nested CES structure as illustrated in Figure 3.1. Moreover, I assume that the individual can consume goods produced both domestically and imported, where imports are combined with domestic goods under the Armington assumption of imperfect substitution (Armington, 1969).

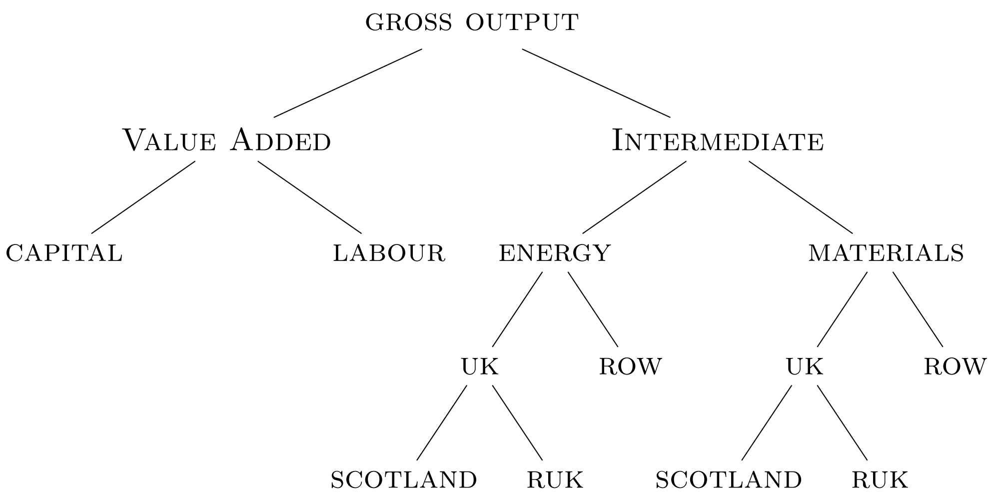
Figure 3.1: The structure of consumption



3.3.2 Production and investment

The production structure reflects the classical KLEM nested CES production function, where capital and labour are combined together to form value added, and energy and materials are combined into intermediate inputs. The combination of intermediate inputs and value added forms gross output. Domestic and imported goods are combined under the Armington assumption (Armington, 1969). This is illustrated in Figure 3.2.

Figure 3.2: The structure of production



The demand functions for capital and labour are obtained from the first order conditions of the CES production function. Following Hayashi (1982), the optimal time path of investment is derived by maximising the value of firms V_t, subject to a capital accumulation function $\dot{K}_t$, so that:

$$\begin{gathered}\text{Max} V_t \sum_{t=0}^{\infty} \left(\frac{1}{1+r}\right)^t \left[\pi_t - I_t \left(1 + g(x_t)\right)\right] \\ \text{subject to } \dot{K}_t = I_t - \delta K_t\end{gathered} \tag{3.3}$$

where 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 problem gives the law of motion of the shadow price of capital, λ_t, and the adjusted Tobin's q time path of investment (Hayashi, 1982).

3.3.3 The labour market, wage bargaining and migration

In this specification of the model, wages are determined within the region in an imperfect competition setting, according to the following wage curve:

$$ln\left[\frac{w_t}{cpi_t}\right] = \varphi - \epsilon ln(u_t) \tag{3.4}$$

where the bargaining power of workers and hence the real consumption wage is negatively related to the rate of unemployment (Blanchflower and Oswald, 2009). In (3.4), $\frac{w_t}{cpi_t}$ is the real consumption wage, φ is a parameter calibrated to the steady state, ϵ is the elasticity of the wage rate related to the rate of unemployment u (Layard et al., 1991).

In the simulations below, the working population is initially assumed fixed, as in Lecca et al. (2014a). However, as I have already noted, regions are much more open systems than nations, and the assumption of a fixed working population is likely to be inappropriate in a regional context. For this reason, I introduce the following migration function (Lecca et al., 2013):

$$nim_t = \zeta - v^u \left[ln(u_t) - ln(\bar{u}^N)\right] + v^w \left[ln(w_t/cpi_t) - ln(\bar{w}^N/\overline{cpi}^N)\right] \quad (3.5)$$

where nim_t is the instantaneous rate of net migration, ζ is a parameter calibrated to ensure zero migration in the first period, and v^u and v^w are elasticicities that measures the response to the differences in logs between regional and national unemployment and real wage rates. In Equation (3.5) net migration flow is positively related to the difference between the log of regional and national real wages and negatively related to the difference between the log of regional and national unemployment rates (Layard et al., 1991; Treyz et al., 1993). This means, for example, that when the regional real wage is higher than the national real wage and/or the regional unemployment rate is lower than its national counterpart, there will be a net in-migration of workers to the region.

3.3.4 Modelling energy efficiency and the rebound effect

I define an increase in energy efficiency as any technological improvement that increases the energy services generated by each unit of physical energy (Lecca et al., 2014a). This implies that the value of energy in efficiency units has risen. Consequently, the household can achieve the same level of utility by consuming the same amount of non-energy goods and services, but less physical energy.

For simplicity, I follow Koesler et al. (2016) and assume that the energy efficiency is given as a public good, with no cost of implementation for the household. This also ensures comparability with the national case analysed by Lecca et al. (2014a).

Following Lecca et al. (2014a) I derive the economy-wide rebound effect in two stages. First, I consider the economy-wide rebound in the household sector (R_C) as:

$$R_C = \left[1 + \frac{\dot{E}_C}{\gamma}\right] \cdot 100 \tag{3.6}$$

where $\dot{E}_C$ measures the proportionate change in household energy consumption, which can be positive or negative, and γ measures the proportionate change in energy efficiency. Because I am analysing the household economy-wide rebound effect in a full general equilibrium system, $\dot{E}_C$ results from a full range of economy-wide adjustments, not just the direct response to the change in the price of the energy service as efficiency increases.[8]

Second, to identify the impact of the energy efficiency improvement on the whole economy (i.e. across all industries, household and domestic institutions) I derive the total rebound R_T as follows:

$$R_T = \left[1 + \frac{\dot{E}_T}{\alpha\gamma}\right] \cdot 100 \tag{3.7}$$

[8]Note that the change in sign from (3.1) and (3.6) is due to the fact that we expect AES to be positive if there is no backfire, which corresponds to a negative proportionate change in household energy consumption.

In this case, $\dot{E}_T$ measures the proportionate change in the energy used in the whole economy, and α initial share of household energy use in the base year.

It is important to notice that the term $\frac{\dot{E}_T}{\alpha\gamma}$ can be expressed as:

$$\frac{\dot{E}_t}{\alpha\gamma} = \frac{\Delta E_T}{\gamma E_C} = \frac{\Delta E_C + \Delta E_P}{\gamma E_C} = \frac{\dot{E}_C}{\gamma} + \frac{\Delta E_P}{\gamma E_C} \tag{3.8}$$

where Δ represents absolute change and the subscript P indicates production. Substituting equations (3.6) and (3.8) into equation (3.7) gives:

$$R_T = R_C + \frac{\Delta E_P}{\gamma E_C} \cdot 100 \tag{3.9}$$

This shows that the total economy-wide rebound will be higher than the household economy-wide rebound if energy consumption in production increases as result of the improvement in energy efficiency in the household sector.

To obtain additional insights from the nature of rebound, I decompose the total economy-wide rebound into the four energy uses included in the model as follows:

$$R_{Tj} = \left[1 + \frac{\dot{E}_{Tj}}{\alpha_j\gamma}\right] \cdot 100 \tag{3.10}$$

where the set j includes coal, gas, electricity and refined oil.

3.3.5 Data and calibration

To calibrate the model I follow a common procedure for dynamic CGE models (Adams and Higgs, 1990), which is to assume that the economy is initially in steady state equilibrium. The structural parameters of the model are derived from the 2009 Social Accounting Matrix (SAM) for Scotland (Emonts-Holley and Ross, 2014), which incorporates the 2009 Scottish Input-Output tables. The Scottish SAM reports information about economic transactions between industries and other aggregate economic agents, namely the Scottish household, the Scottish Government, and corporate sectors, and accounts for imports and exports to the rest of the UK (RUK) and the rest of the world (ROW). For this paper, I aggregate the SAM to 21 industries,[9] including four energy sectors, gas, electricity, coal and refined oil.

The SAM constitutes the core dataset of the AMOS-ENVI model. However other parameters are required to inform the model, such as elasticities, and shares parameters. These are either exogenously imposed, based on econometric estimation or best guesses, or determined endogenously through the calibration process.

To observe the adjustment of all the economic variables through time, simulations are solved simultaneously for 50 periods (years). I introduce a 5% costless, exogenous and permanent increase in the efficiency of energy used in household consumption. Following this initial 'shock', all the variables start to adjust over time until they reach a new steady state equilibrium. Results are reported for two conceptual periods: the short-run, where the working population and capital stocks are fixed, and the long-run, which corresponds to the new steady state equilibrium characterised by no further changes in sectoral capital stocks and population. When appropriate, I also report period by period adjustments.

[9]See Appendix B for the full list of sectors included in the model.

3.4 Simulation scenarios

Simulations in this paper reflect four main scenarios, summarised in Table 3.1. All of the simulations use the AMOS-ENVI model, calibrated on Scottish data, as outlined in Section 3.3.

Table 3.1: Summary of Simulations

	No Migration	Migration
Standard *cpi*	Scenario 1	Scenario 2
Adjusted *cpi*	Scenario 3	Scenario 4

Scenario 1. In Scenario 1, I use the version of the AMOS-ENVI model that is most comparable to Lecca et al. (2014a), in that the working population is assumed fixed. The *cpi* is calculated using the standard method.

Scenario 2. In Scenario 2, I repeat the same simulations of Scenario 1, using the AMOS-ENVI model with standard *cpi* but introducing the migration function described in equation (3.5).

Scenario 3. Here I modify Scenario 1 by assuming that the energy efficiency improvement in the household sector is directly reflected in the wage determination process (equation (3.4)), because the *cpi* effectively falls as a consequence of the improvement in energy efficiency Lecca et al. (2014a). This is implemented by adjusting the *cpi* to include the price of energy measured in efficiency units as follows:

$$p_E^F = \frac{p_E}{1+\gamma} < p_E \text{ for } \gamma > 0 \tag{3.11}$$

so that

$$cpi^{\tau} = cpi(p_{NE}, p_E^F) \tag{3.12}$$

In (3.11) and (3.12) p_{NE} is the price of non-energy goods, p_E is the price of energy goods measured in natural units and p_E^F is the price of energy goods measured in efficiency units. When the price of energy in natural units is constant, an increase in efficiency decreases the price of energy in efficiency units, reducing therefore the cpi^{τ} which directly affects the real wage as determined in equation (3.4). As in Scenario 1, the working population is fixed.

Scenario 4. In Scenario 4, I repeat the simulation carried out in Scenario 3, with the adjusted *cpi* (as in equations 3.11 and 3.12), but now allowing for endogenous migration (equation 3.5).

To summarise, Scenarios 1 and 3 differ from one another in the way the *cpi* is calculated but they make the same fixed working population assumption. Scenarios 2 and 4 repeat the same simulations as 1 and 3 but assuming full flow migration.

As in Lecca et al. (2014a) all the short-run simulations are carried out using two alternative estimates of the elasticity of substitution between consumption of energy and non-energy goods, the short-run elasticity and the long-run elasticity.[10] There are two main reasons for this approach. Firstly, there might be some degree of inertia in the adjustment of household consumption, that would be reflected in a lower response to an energy price change over the short period. Secondly, the energy efficiency improvement may come through an investment in durable goods. In this case, in order to access the efficiency improvement an adjustment of household capital stock would be necessary, and this is generally a

[10]These are based on the recent estimation carried out by Lecca et al. (2014a) and are respectively 0.35 and 0.61

long-run adjustment. Apart from this, differences among the four Scenarios are reflected in the way the *cpi* is calculated and by the degree of openess of the labour market as follows.

All of these simulations are based on the fiscal arrangements that existed prior to April 2016. Scotland is now in the process of moving to a significantly more devolved fiscal system: in particular, the Government's budget will become dependent on Scottish income tax revenues, which vary directly with economic activity (Scotland Act, 2016). In order to reflect this change I repeat the simulations from Scenario 1, but assume that the Scottish Government maintains a balanced budget so that any increased tax revenues resulting from the stimulus to economic activity generated by the increase in energy efficiency may be spent by the Government or used to reduce the rate of income tax.

3.5 Results

3.5.1 Scenario 1: the standard model with no migration

Table 3.2 summarises short-run (SR) and long-run (LR) results of simulations for Scenario 1. Recall that ε is the elasticity of substitution in consumption between energy and non-energy goods, from equation (3.2). In the first column I report short-run results using the short-run elasticity of substitution ($\varepsilon = 0.35$). Following the energy efficiency improvement, household energy consumption decreases by 2.67%, while household consumption increases by 0.33%. The higher consumption puts upward pressure on the *cpi*, making domestic products more expensive and reducing

Table 3.2: % change in the key economic variables in Scenario 1

Elasticity of substitution	ε SR	ε LR	ε LR
Time period	Short-run		Long-run
GDP	0.04	0.03	0.11
Consumer Price Index	0.09	0.09	0.04
Unemployment Rate	-0.25	-0.21	-0.45
Total Employment	0.06	0.05	0.11
Nominal Gross Wage	0.12	0.11	0.09
Real Gross Wage	0.03	0.02	0.05
Households' Consumption	0.33	0.32	0.40
Investments	0.14	0.16	0.11
Exports	-0.13	-0.12	-0.06
Non-Energy Output	0.07	0.06	0.14
Energy Output	-0.41	-0.23	-0.46
Energy Use	-0.88	-0.47	-0.61
Energy Demand in Production	-0.22	-0.11	-0.30
Households' Consumption of Energy	-2.67	-1.43	-1.48
Households' Consumption of non-Energy	0.52	0.44	0.52
Household Rebound	46.57	71.45	70.33
Economy-wide Rebound	28.40	61.92	50.08

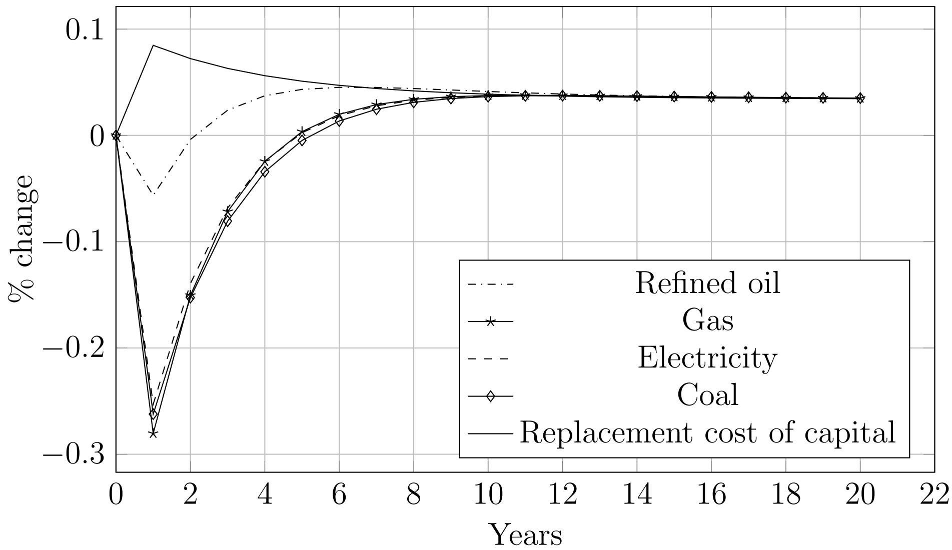
international competitiveness. On the other hand, this shift in demand stimulates investment in non energy sector, so that total investment increase by 0.14% and the output of non energy producers rises by 0.07%. This impacts the labour market, where total employment increases by 0.06%, unemployment decreases by 0.25% and the real wage is 0.03% higher.

The second column of Table 3.2 reports short-run results using the long-run elasticity ($\varepsilon = 0.61$). When the elasticity of substitution is low, there is stronger complementarity between energy and non-energy goods. As the elasticity of substitution increases, the degree of substitutability is greater and consumers substitute more towards energy, because its price in efficiency units has reduced. This is reflected in a smaller decrease in energy consumption of -1.43% and a smaller increase in household non-energy consumption, of 0.44%. Given the lower switch in consumption, the economic stimulus is smaller, reflecting the fact that, in the Scottish case, the expenditure in non-energy goods has a higher impact on the economy than the same spending on energy goods. This is because energy goods are typically more import-intensive that non-energy goods, and therefore a higher spending on non-energy goods has a higher impact on the regional economy.

Long-run results are reported in the third column of Table 3.2. Scottish GDP increases by 0.11% relative to what it would have been without the efficiency improvement. The fall in household energy demand impacts energy demanded by industries, which decreases by 0.22%. This is mostly due to the decreased activity in energy intensive energy suppliers. In fact, energy production and supply require lots of energy: when household demand less energy, less energy is supplied, and energy producers/suppliers reduce their energy use. For these reasons, the output of energy sectors decreases by 0.41%. Moreover, the initial reduction in demand for energy (as efficiency increases) causes a reduction in the return on capital in energy supply so that, over time, energy suppliers reduce their capacity. This is what Turner (2009) calls the 'disinvestment' effect.

This can be clearly seen in Figure 3.3 where I plot the shadow price of capital for the energy sectors and the replacement cost of capital. In

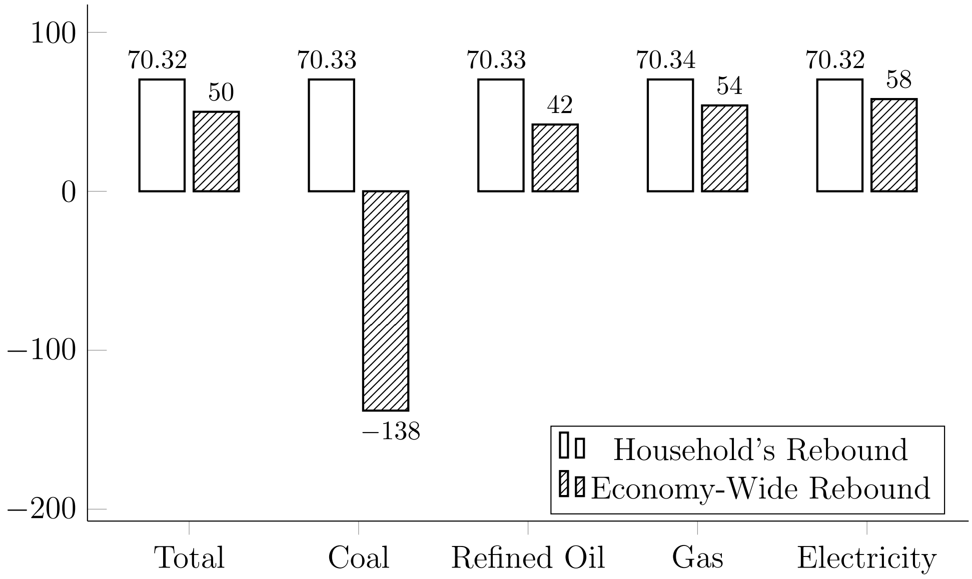
Figure 3.3: Transitions of shadow price of capital in energy sectors and replacement cost of capital



the short-run the shadow price of capital of each sectors drops below the replacement cost of capital, so that Tobin's q is lower than 1 and therefore the cost of replacing the capital is higher than the value of the stock, and it is not profitable to invest. Over time, the price of energy rises again, allowing the shadow price of capital to recover and converge asymptotically to the replacement cost of capital, so that Tobin's q again approaches unity. Because of the net contraction in industrial energy use, the overall long-run economy-wide rebound effect (50.08%), is smaller than the general equilibrium household rebound effect (70.33%).

Interesting insights can be obtained by disaggregating the rebound effects for each energy sector using equation (3.10). In Figure 3.4 I plot household and economy-wide rebound effects disaggregated into coal, refined oil electricity and gas. There is significant variation in the economy-wide rebound in the use of different types of energy, reflecting the different composition in the energy used in the production side of the economy.

Figure 3.4: Long-run Households and Economy-Wide Rebound Effects in Scenario 1



The economy-wide rebound in the use of electricity and gas is higher than the total economy-wide rebound, while refined oil rebound it is lower. There is a negative rebound in the use of coal, implying that the energy saved in this sector is higher than the expected savings. It is important to notice that household and firms do not usually consume coal directly, but rather they consume electricity produced by coal-fired power stations. When the demand for electricity drops, power stations cut the demand for coal, and this dramatically reduces the use of such fuel, explaining the negative rebound.

Results from Scenario 1 appear to be in line with findings in Lecca et al. (2014a). However, given the higher degree of openness of the goods market of regions, exports decrease in Scotland by more than in the national case.[11] The increase in household energy efficiency yields a double

[11]In the UK case, exports decrease by 0.08 in the short run and 0.04 in the long run (Lecca et al., 2014a).

dividend or multiple benefit of increased economic activity (and employment) and a reduction in total energy use across all simulations in Scenario 1.

3.5.2 Scenario 2: the standard model with migration

In this Scenario I repeat the simulations of Scenario 1, but include the migration function described by equation (3.5). Results for key variables are reported in Table 3.3. To facilitate the comparison to the no-migration case, I add a fourth column reminding us of the long-run results from Scenario 1. Short-run results are quite close to the previous case, because there is no migration in the first period, therefore a comparison is not necessary.[12]

In the long-run there is a higher increase in GDP (0.17%), reflecting the higher level of capital stock (0.17%) and employment (0.18%). The differences are driven by the effect of the net in-migration triggered by the initial drop in the unemployment rate and by the rise in the real wage. Following the energy efficiency improvement, workers start to migrate into the region in response to wage and unemployment differentials from the second period. This puts downward pressure on wages, and increases the unemployment rate according to the wage setting curve (equation 3.4). The dynamics of these variables can be seen in Figure 3.5 where I plot the time path of the real wage, unemployment, *cpi* and exports.

The real wage falls and the unemployment rate increases until they

[12]Short-run results are not exactly the same of Scenario 1 as in this model I have forward-looking agents, therefore some of the effects of migration are anticipated.

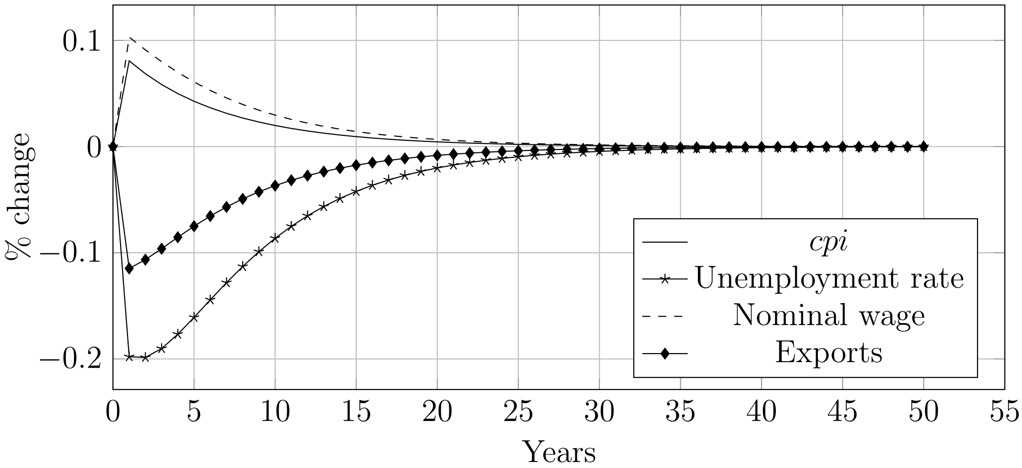
Table 3.3: % change in the key economic variables in Scenario 2

Elasticity of substitution	ε SR	ε LR	ε LR	
Time period	Short-run		Long-run	*LR Sc.1*
GDP	0.04	0.03	0.17	*0.11*
Consumer Price Index	0.08	0.08	0.00	*0.04*
Unemployment Rate	-0.24	-0.20	0.00	*-0.45*
Total Employment	0.06	0.05	0.18	*0.11*
Nominal Gross Wage	0.11	0.10	0.00	*0.09*
Real Gross Wage	0.03	0.02	0.00	*0.05*
Households' Consumption	0.30	0.30	0.42	*0.40*
Investments	0.15	0.16	0.17	*0.11*
Export	-0.12	-0.11	0.00	*-0.06*
Non-Energy Output	0.07	0.06	0.19	*0.14*
Energy Output	-0.41	-0.23	-0.41	*-0.46*
Energy Use	-0.89	-0.48	-0.57	*-0.61*
Energy Demand in Production	-0.22	-0.12	-0.24	*-0.30*
Households' Consumption of Energy	-2.70	-1.45	-1.47	*-1.48*
Households' Consumption of non-Energy	0.49	0.41	0.54	*0.52*
Household Rebound	46.03	70.94	70.51	*70.33*
Economy-wide Rebound	27.65	61.22	53.48	*50.08*

both approach zero, when the labour market reaches its long-run equilibrium. Similarly, the *cpi* returns to its base year value, allowing exports to increase again until the original competitiveness is completely restored. This is a crucial result, because it shows that unlike in Scenario 1 and in Lecca et al. (2014a), where the higher *cpi* crowds out exports, in a regional economy with free movement of workers, and flow migration, this negative effect on international competitiveness disappears in the long-run, due to the effect of migration on prices.

The restored long-run competitiveness contributes to give additional

Figure 3.5: Adjustment path of *cpi*, unemployment rate, nominal wage and exports



momentum to the economic stimulus. This is reflected in a rise in output of non energy sectors of 0.19%. But because these activities use energy as an input in production, the energy output reduction is slightly less than in previous scenario, likewise the decrease in total energy use. On the other hand, household energy consumption decreases by 1.47%, which is quite close to the outcome in Scenario 1. This is because the lower real wage decrease household's labour income, partly mitigating the response in consumption. For this reasons, only the calculated economy-wide rebound effect is higher, (53.5%), while the household rebound is hardly affected.

The zero variation in prices over the long-run indicates a pure demand response to the introduction of the energy efficiency improvement, similar to what we would expect in an Input-Output modelling framework (McGregor et al., 1996). The economic expansion observed in this Scenario is entirely demand-driven. Again, the increase in household energy efficiency generates a double dividend, although here with a greater stimulus to economic activity and smaller fall in total energy use than in Scenario 1.

3.5.3 Scenario 3: the model with adjusted cpi and no migration

In Scenarios 1 and 2, the energy efficiency improvement is modelled so as to reflect a simple change in consumer's taste, with the macroeconomic effects being driven by the change in consumption patterns.

Here I consider the case where the increase in household energy efficiency use is reflected in an overall reduction in the cost of living, by adjusting the *cpi* to include the price of energy calculated in efficiency units according to equations (3.11) and (3.12).

Key results for this case are summarised in Table 3.4. Unlike Scenario 1, where the *cpi* increases immediately and remains above the initial level for all 50 periods, and Scenario 2 where it returns to its base year value in the long-run, here the *cpi* decreases both in the short-run and in the long-run, given the lower price of energy in efficiency units. Consequently the nominal wage decreases by 0.16% in the short-run and by 0.22% in the long-run, but because of the lower *cpi* the real wage increases by 0.9% and 0.16% respectively.

The lower price of goods produced domestically stimulates the demand for Scottish goods from the rest of UK and the rest of the World, and although in the short-run exports fall by 0.5% (which is less than what we observed in Scenarios 1 and 2), in the long-run they increase by 0.16%. This difference is crucial in terms of comparison with the standard case, because it shows that when the energy efficiency improvement

Table 3.4: % change in the key economic variables in Scenario 3

Elasticity of substitution	ε SR	ε LR	ε LR
Time period	Short-run		Long-run
GDP	0.12	0.12	0.33
Consumer Price Index	-0.25	-0.26	-0.38
Unemployment Rate	-0.80	-0.76	-1.38
Total Employment	0.20	0.19	0.34
Nominal Gross Wage	-0.16	-0.17	-0.22
Real Gross Wage	0.09	0.09	0.16
Households' Consumption	0.30	0.30	0.47
Investments	0.44	0.46	0.32
Export	-0.05	-0.05	0.16
Non-Energy Output	0.15	0.14	0.34
Energy Output	-0.38	-0.20	-0.28
Energy Use	-0.85	-0.44	-0.46
Energy Demand in Production	-0.17	-0.07	-0.10
Households' Consumption of Energy	-2.71	-1.48	-1.45
Households' Consumption of non-Energy	0.50	0.41	0.59
Household Rebound	45.74	70.39	71.07
Economy-wide Rebound	31.00	63.76	63.00

is reflected in less pressure for higher wages, we have a long-run increase in competitiveness, similarly to Allan et al. (2007) and Turner (2009) which focus on industrial energy efficiency. It is also important to notice that, given the greater openess of the goods market of regions, the long-run increase in exports is significantly higher than that reported in Lecca et al. (2014a).

The increase in competitiveness along with the switch in the aggregate demand triggers a bigger economic stimulus that is reflected in most of the key macroeconomic indicators. For example, investment increases by 0.44% in the short-run and 0.32% in the long-run. Consequently, the increase in labour and capital used in production has a positive effect on output which increases by 0.12% in the short-run and by 0.33% in the long-run.[13]

There is a higher demand for energy by industry sectors. Intuitively, when the production of goods and services increases, industry consumes more energy in the production process. However, in the household sector the decrease in energy consumption is in line with what was reported for Scenarios 1 and 2. For this reason, the household rebound is only around 0.5% higher than the standard no migration case. However, the economy wide rebound is higher in Scenario 3, both in the short-run (31%) and in the long-run (63%), reflecting the higher use of energy for industrial purposes. This suggests that the bigger stimulus to economic activity observed in Scenario 3 results in overall a higher use of energy and calculated rebound effect, although there is still a double dividend in that economic activity rises while energy use falls.

Again, here we may argue that in fact there are multiple dividend or benefits from energy efficiency. First, energy efficiency improvements reduce to some extent final energy demand. Second, it increase household income, reducing poverty and fuel poverty and stimulating the aggregate demand. Third, the demand stimulus has an impact on other sectors of the economy (multiple benefits). These are enhanced when the *cpi* is adjusted to reflect the reduction in prices of energy in efficiency units.

[13]In Lecca et al. (2014a) GDP increases by 0.1 in the short-run and 0.24 in the long-run.

3.5.4 Scenario 4 : the case of migration and adjusted cpi

In the final case, I include both the adjusted *cpi*, equations (3.11) and (3.12), and the migration function, equation (3.5). Results from these simulations are reported in Table 3.5.

Table 3.5: % change in the key economic variables in Scenario 4

Elasticity of substitution	ε SR	ε LR	ε LR
Time period	Short-run		Long-run
GDP	0.12	0.11	0.53
Consumer Price Index	-0.27	-0.28	-0.49
Unemployment Rate	-0.77	-0.73	0.00
Total Employment	0.19	0.18	0.54
Nominal Gross Wage	-0.18	-0.19	-0.49
Real Gross Wage	0.09	0.08	0.00
Households' Consumption	0.22	0.22	0.53
Investments	0.46	0.47	0.50
Export	-0.03	-0.02	0.35
Non-Energy Output	0.14	0.13	0.51
Energy Output	-0.38	-0.18	-0.07
Energy Use	-0.88	-0.42	-0.26
Energy Demand in Production	-0.18	-0.06	0.10
Households' Consumption of Energy	-2.79	-1.55	-1.27
Households' Consumption of non-Energy	0.41	0.33	0.65
Household Rebound	44.17	71.62	74.53
Economy-wide Rebound	28.38	65.36	78.59

In this case, I observe the greatest economic expansion, reflected in most of the macroeconomic indicators. GDP rises by 0.53% in the long-run, driven by a 0.5% increase in capital stock and 0.54% in employment.

The latter is determined by the combined effects of migration and adjusted *cpi* on the labour market.

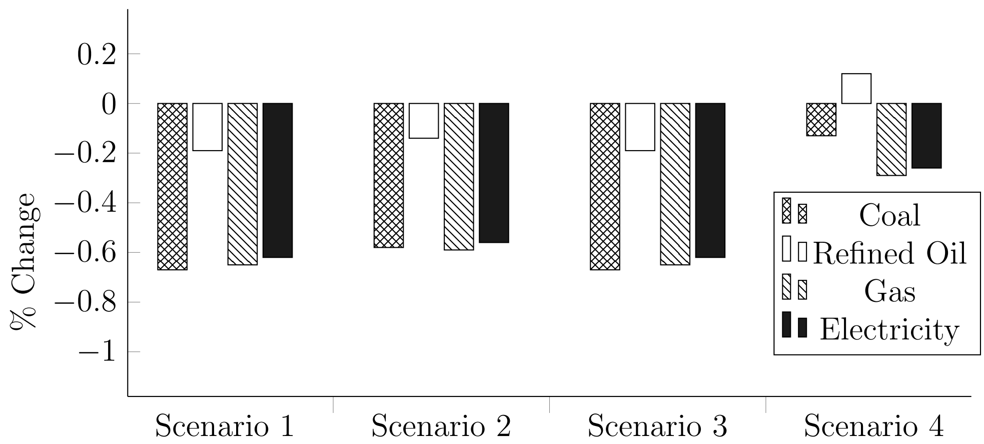
In the short-run, unemployment decreases by 0.77%, and although the nominal wage falls by 0.18%, the real wage increases by 0.09%, because of the lower *cpi*. This triggers interregional net in-migration. Similarly to Scenario 2, the real wage and the unemployment rate start to adjust until they converge to their initial level in the long-run. This is different from the adjusted *cpi* case with no migration, where in absence of additional workers from abroad the unemployment rate drops by 1.48% in the long-run. However, in this case the *cpi* does not return to zero in the long-run, but it behaves as in Scenario 3, decreasing in the long-run by 0.49%.

The lower *cpi* encourages individuals to consume more. Household's consumption increases by 0.22% in the short-run, and by 0.53% in the long-run. Because goods produced in Scotland become cheaper for foreign buyers, there is a by 0.35% long-run increase in exports, similarly to Scenario 3.

The increased competitiveness, along with the shift in domestic aggregate demand, puts upward pressure on the demand for energy in all the productive sectors. In the long-run, energy output decreases by 0.07%, and the overall use of energy in the economy decreases by 0.26%, due to a drop in household energy consumption by 1.27%. However, industries raise their energy demand, and unlike all the other scenarios there is a long-run increase in industrial energy use (by 0.1%) . This is the most interesting result of this Scenario because it underlines that under certain conditions, an increase in energy efficiency in the household sector may lead to an actual increase in industrial energy consumption.

In Figure 3.6 I plot long-run investment in gas, refined oil, coal and electricity in the four Scenarios. In the first three cases investments are negative in all the energy sectors due to the disinvestment effect described in Scenario 1 (Turner, 2009). However, in Scenario 4 the contraction in investment is lower in gas, coal and electricity, but investment is positive in the oil sector, which is quite important in the Scottish economy.

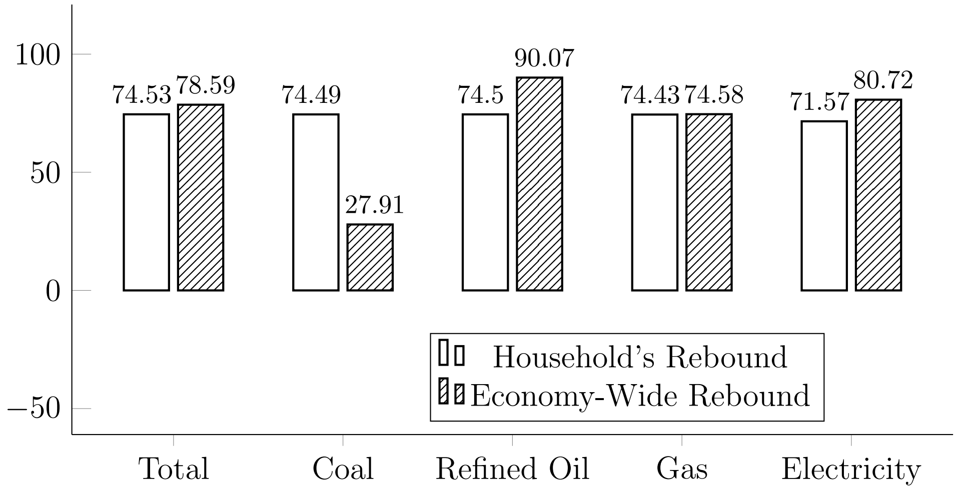
Figure 3.6: Long-run investment in the energy sectors



Because energy used by industries increases in the long-run, the long-run economy-wide rebound effect is higher (though marginally) than the household rebound effect, exactly as we would expect (giving equation (3.9)).

In Figure 3.7 I plot the household's and economy-wide rebound effect disaggregate by energy sectors. The economy-wide rebound in oil and electricity is higher than the household rebound, reflecting the rise in the use of these fuels in industry. Unlike Scenario 1, where I observed a negative rebound in the coal sector, (see Figure 3.4), in this case there is a positive 27.9% economy-wide rebound indicating a rise in the demand for such fuel, but there is again a double dividend.

Figure 3.7: Long-run Household and Economy-Wide Rebound Effects by energy sectors in Scenario 4



3.6 Discussion: trading-off economic benefits and rebound

Results from the four Scenarios show that increasing household energy efficiency in Scotland by 5% does stimulate the Scottish economy. However, there is a clear trade-off between economic benefits and achieved energy savings, which varies across scenarios, depending on whether the efficiency improvement influences the *cpi* and the wage bargaining process, and whether there is migration.

Table 3.6 summarises the calculated long-run rebound and household rebound effects, and the long-run percentage change in GDP in the four cases. In Scenario 1, with the standard *cpi* and no migration, the economic expansion is triggered by a pure demand shock, which puts upward pressure on domestic prices, crowding out exports. In this case, the calculated household rebound effect is 70.33%, which reduces to 50.08% when the whole economy is considered, so that, overall, 50.08% of the

Table 3.6: Long-run economy wide rebound, household rebound, and percentage change in GDP under the four Scenarios

	No migration			Migration		
	R_C	R_T	GDP	R_C	R_T	GDP
Standard *cpi*	70.33	50.08	0.11	70.51	53.48	0.17
Adjusted *cpi*	71.07	63.00	0.33	74.53	78.59	0.53

5% expected energy savings will be offset by increased energy demand. In this Scenario, GDP increases by 0.11%.

In Scenario 2, the energy efficiency change delivers again what is effectively a pure demand shock, with no changes in competitiveness the long-run, further stimulating economic activity. This results in a greater increase in GDP of 0.17%. For this reason, while the household rebound is quite close to the level of Scenario 1, the overall rebound increases to 53.48%, reflecting a higher energy demand by industries.

In Scenario 3, where the *cpi* is adjusted to include the price of energy in efficiency units, but there is no migration, I observe an increase in competitiveness in the long-run and the type of stimulus is similar to the productivity-led growth observed in previous work focussed on energy efficiency in production (Allan et al., 2007; Turner, 2009). In this case, the household rebound effect is 71.07%, very close to Scenarios 1 and 2. However, given the stimulus to supply, industries demand more energy, delivering an overall rebound of 63%, and a 0.33% rise in GDP, which is greater than Scenarios 1 and 2.

Lastly, in Scenario 4, the combination of the adjusted *cpi* and migration causes the largest supply side response, reproducing again the characteristics of a productivity-led stimulus, and triggering the greatest economic expansion. In fact, GDP rises by 0.53% and as we would expect, the economy wide-rebound is 78.6%, which is higher than the household's rebound.

The trade-off between economic benefits and energy demand reduction is reflected in the fact that the higher is the economic stimulus received from the more efficient use of energy the higher is the rebound effect. However, in none of these scenarios does the calculated rebound effect offset completely the expected energy reduction (i.e there is no 'backfire' effect), indicating that increasing energy efficiency typically generate a double dividend of an increase in economic activity and a reduction in energy use. Nonetheless, the stronger the economic stimulus, the smaller the reduction in energy use and the greater the extent of rebound.

3.7 Towards new fiscal powers for Scotland

In all the Scenarios above, we have treated Scotland as a regional economy that has no devolved taxes, which was the case until very recently. In these circumstances Government expenditure is entirely exogenous and tax revenues accrue to the central Government in Westminster.

However, with the gradual devolution of fiscal powers from UK to Scotland, this will be an increasingly inaccurate representation of the Scottish fiscal framework. Given that we are still in a transition period, here I illustrate the key principles by focussing on the simple case where the Scottish Government maintains a fixed government budget according to this simple relation:[14]

[14] This is a simplified version of Equation (C56) in Appendix A.

$$\overline{GOVBAL_t} = GY_t - GEXP_t \tag{3.13}$$

Equation (3.13) indicates that at each period the Government's budget $GOVBAL$ is equal to Government income, GY, minus Government expenditure, $GEXP$. In order to keep $GOVBAL$ constant the Government can either increase/decrease its income by varying the rate of income tax or increase/decrease its current expenditure. I assume that whenever Government expenditure varies, the change is distributed across sectors, according to the baseline Government's expenditure shares.

To illustrate the implications of introducing a balanced budget constraint in the Scottish Economy I repeat the simulations of Scenario 1, which reflects a 5% increase in household's energy efficiency assuming no interregional migration.

I explore 3 sub-scenarios, FIXGOV, FIXBAL, TAX. The FIXGOV Scenario replicates Scenario 1 by assuming fixed Government expenditure with tax revenues accruing to Westminster. In the FIXBAL case I assume that tax revenues are devolved and the Scottish Government maintains a given fiscal balance by varying public expenditure in response to any changes in tax revenues. In the TAX scenario I assume that the any stimulus to the economy, and to tax revenues, is used to reduce the income tax rate so as to maintain a fixed fiscal balance.

FIXGOV results are reported in the first column of Table 3.7. The economic stimulus from the improved household's energy efficiency generates additional tax revenue for the Scottish Government. However, because the expenditure is fixed and revenues accrue to the UK, not to the Scottish Government, the Scottish Government's fiscal balance increases

Table 3.7: Comparing impacts of a 5% increase in household energy efficiency under different fiscal regimes

	FIXGOV		FIXBAL		TAX	
	SR	**LR**	**SR**	**LR**	**SR**	**LR**
GDP	0.04	0.11	0.05	0.14	0.05	0.19
Consumer Price Index	0.09	0.04	0.11	0.05	0.11	0.02
Unemployment rate	-0.25	-0.45	-0.32	-0.61	-0.34	-0.76
Total employment	0.06	0.11	0.08	0.15	0.08	0.19
Nominal Gross Wage	0.12	0.09	0.14	0.12	0.12	0.04
Real Gross Wage	0.03	0.05	0.04	0.07	0.04	0.09
Household's Consumption	0.33	0.40	0.37	0.44	0.41	0.52
Investment	0.12	0.11	0.15	0.13	0.19	0.19
Exports	-0.13	-0.06	-0.15	-0.08	-0.15	-0.03
Non-Energy Output	0.07	0.14	0.09	0.17	0.09	0.21
Energy Output	-0.41	-0.46	-0.41	-0.46	-0.40	-0.39
Energy Use	-0.88	-0.61	-0.86	-0.59	-0.85	-0.52
Energy Demand by Industries	-0.22	-0.30	-0.22	-0.28	-0.21	-0.22
Households' Energy Consumption	-2.67	-1.48	-2.63	-1.44	-2.60	-1.37
Government Expenditure	-	-	0.06	0.16	-	-
Government Balance	56.7	124.8	-	-	-	-
Income Tax	-	-	-	-	-0.10	-0.26
Household Rebound	46.57	70.33	47.32	71.10	48.08	72.66
Economy Wide Rebound	28.40	50.09	29.53	51.80	30.82	57.40
Energy productivity	0.79	0.81	0.80	0.82	0.79	0.78

both in the short-run and in the long-run.

In the FIXBAL case, the additional income is used to increase the Scottish Government's current expenditure by 0.06% in the short-run and 0.16% in the long-run. The additional resources are now recycled into the economic system under the form of additional demand, further stimulating the economy. For this reason GDP increases by more than in the FIXGOV case, both in the short-run (by 0.05%) and in the long-run (by 0.14%). Similarly we observe a greater increase in employment, investment and output from industries. The additional government spending puts additional pressure on domestic prices, further reducing exports. Consistently with what we observed in the other Scenarios of this paper, the greater economic expansion is also associated with bigger rebound effects.

Finally, in the TAX case, the results of which are reported in the third column of Table 3.7, the Government uses the additional resources to reduce the income tax rate. In this case we have a simultaneous demand and supply stimulus.

Firstly, tax reduction increases household's disposable income so that consumption rises by 0.41% in the short-run and 0.52% in the long-run. Secondly, the reduced taxation increases the post-tax real consumption wage, so that there is downward pressure on wage bargaining, reducing the price of labour and stimulating employment and production. The long-run nominal wage increases by 0.04% while it was 0.09% in the standard case. However, the real wage increases by 0.09% which is more that the FIXGOV and FIXBAL scenarios.

Because production is stimulated by the lower price of labour, industries produce more output, increasing also the use of other inputs, including energy. For this reason, the economy wide rebound is substantially higher than in the FIXGOV case, especially in the long-run (57.4%).

3.8 Conclusions

The simulation results reported in this paper lead me to five general conclusions.

First, increasing energy efficiency in Scottish households stimulates the regional economy. However, the scale and nature of the stimulus differs depending on the precise specification of the shock. The key issue here is whether the *cpi* is adjusted to reflect the lower price of an efficiency unit of energy. If the *cpi* is not adjusted the stimulus to the economy from the increase in household energy efficiency takes the form of a pure demand shock; if the adjusted *cpi* is relevant there is a simultaneous demand and supply side stimulus.

Second, moving from a national to a regional context, in particular by opening the labour market to migration typically results in a greater economic stimulus, because it recovers the initial loss in competitiveness in the long-run. Even if migration is insufficient to fully restore initial wage and unemployment rates, the direction of the impact would be the same: the presence of migration reinforces the impact of any demand or supply side stimulus on the economy.

Third, the stimulus to household energy efficiency always reduces energy consumption. So household energy efficiency increases typically deliver a double dividend of reductions in energy demands (and emissions) and increases in economic activity. However, when the economic expansion is higher, the difference between potential energy savings and actual energy savings (rebound effects) is also higher, indicating a trade-off between actual energy savings and economy benefits. So energy efficiency stimuli do help with the achievement of energy or emission targets, but the extent to which it does so is generally inversely related to scale of the associated economic expansion.

Fourth, the greater regional fiscal autonomy reinforces the economic stimulus, since in this case increases in regional economic activity stimulate the regional Government's tax revenues. In fact, these can be used either to increase public spending, or to reduce Scottish tax rates. However, greater autonomy therefore also implies that the extent of energy saving will be reduced. This is significant given that Scotland is in the process of acquiring a substantially enhanced degree of fiscal autonomy.

Finally, the triggers of the rebound effect are typically the drivers of the economic stimulus. Further investigations should explore ways to minimise the magnitude of the rebound effect, without sacrificing the gains in terms of economic welfare.

Chapter 4

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

4.1 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-González, 2011). Where different household income groups are identified, emphasis has tended to be placed on how rebound effects are driven by changes in real income following an energy efficiency improvement, that 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 (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

[1] In warmer climates, cooling may be a greater concern than heating but 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.

value to the economy that is created as result of ‘investing’ in increased energy efficiency. I consider this in the context of a general equilibrium argument. That is, I 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.

I 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, I 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 4.2 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. I focus on the extent to which wider economic expansionary and socio-economic arguments have been made. Section

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

4.3 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 4.4 describes the UK CGE model that I 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 4.5 details the simulation scenarios that are then implemented in Section 4.6, where I discuss the results. In Section 4.7 I test the sensitivity of the results to the assumption of a common elasticity of substitution across different household income groups. Finally, Section 4.8 draws conclusions and considers policy implications.

4.2 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; Freire-González, 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 CO2 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 due to an increase in energy efficiency, 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., 2014a).

Duarte et al. (2016) and Lecca et al. (2014a) 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. (2014a) take 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. (2014a) 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. (2014a) 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. (2014a) 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. (2014a) 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. (2016) 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

[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.

is on potential reduction of CO2 emissions, Duarte et al.'s (2016) 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 IEA (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 I focus on how support of energy efficiency programmes in the household sector may be justified through 'pay back' delivered by macroeconomic expansion.

4.3 Issues for a policy context

If we broaden the 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]

In the current paper, I 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, I 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 improve-

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

[5]As I 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. This is explored in Chapter 3 and to some extent in Chapter 5.

ment 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, I 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,

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

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]

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 I 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.

4.4 Model and Data

I 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, I assume that invest-

[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 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.

ments are made by profit maximising forward-looking agents while (here five) representative households (distinguished as income quintile groups) are myopic. This is 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 I provide a description of the main characteristics of the model.[10]

4.4.1 Consumption

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

$$C_{h,t} = YNG_{h,t} - SAV_{h,t} - HTAX_{h,t} - CTAX_{h,t} \qquad (4.1)$$

In (4.1) total consumption C is a function of income YNG, savings SAV, income taxes $HTAX$, and taxes on consumption $CTAX$.

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

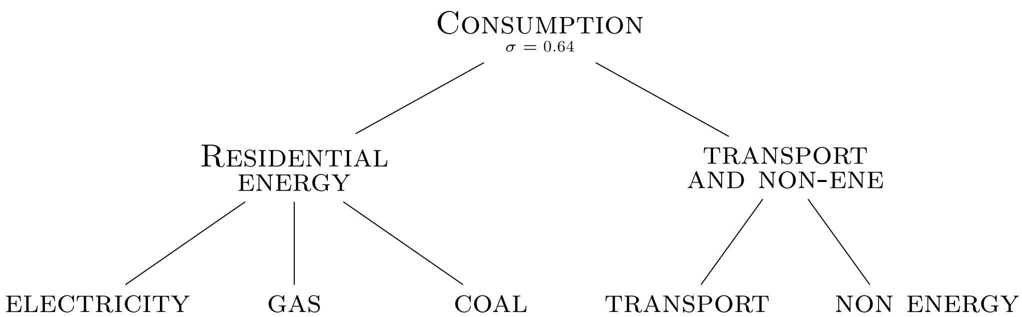
[9]It could be argued that lower income households are more myopic than higher income households. Although this is a reasonable observation, I assume the same behaviour for all households given that a) I focus my attention on lower income households and b) long-run results are identical, regardless of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

[10]The full mathematical description of the model is reported in Appendix A.

$$C_{h,t} = \left[\delta_h^E (\gamma EC_{t,h})^{\frac{\varepsilon_h - 1}{\varepsilon_h}} + (1-\delta_h^E) TNEC_{h,t}^{\frac{\varepsilon_h - 1}{\varepsilon_h}} \right]^{-\frac{\varepsilon_h}{\varepsilon_h - 1}} \qquad (4.2)$$

In (4.2) ε is the elasticity of substitution in consumption, and measures the extent to which consumers substitute energy goods, EC, for non-energy and transport consumption, $TNEC$, $\delta \in (0,1)$ is the share parameter, and γ is the efficiency parameter of 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. (2014a).[11]

Figure 4.1: The structure of consumption



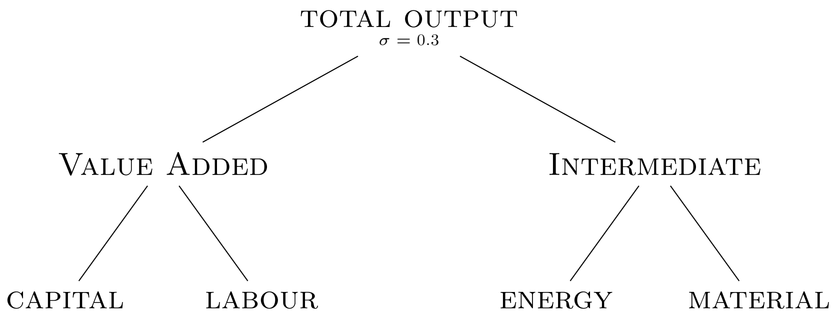
The consumption of residential energy includes electricity, gas and coal, as shown in Figure 4.1, although the share of coal consumed by households represents less than 0.01% of total energy consumption. Within the energy bundle, given that I do not focus on inter-fuel substitution in the analysis below, I impose a small but positive elasticity.

[11] However, as noted in the analysis below, I have conducted sensitivity analysis where I introduce different values for different household income groups.

4.4.2 Production and investment

The production structure is characterised by a capital, labour, energy and materials (KLEM) nested CES function. As I show in Figure 4.2 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.

Figure 4.2: The structure of production



Following Hayashi (1982), I 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:

$$\begin{gathered} \text{Max} V_t \sum_{t=0}^{\infty} \left(\tfrac{1}{1+r}\right)^t \left[\pi_t - I_t \left(1 + g(x_t)\right)\right] \\ \text{subject to } \dot{K}_t = I_t - \delta K_t \end{gathered} \tag{4.3}$$

where 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).

4.4.3 The labour market

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

$$ln\left[\frac{w_t}{cpi_t}\right] = \varphi - \epsilon ln(u_t) \tag{4.4}$$

where the real consumption (after tax) wage is negatively related to the rate of unemployment (Blanchflower and Oswald, 2009). In (4.4), $\frac{w_t}{cpi_t}$ is the real consumption wage, φ is a parameter calibrated to the steady state, ϵ is the elasticity of wage rate related to the rate of unemployment u. The working population is assumed to be fixed and exogenous.

4.4.4 Government

The Government collects taxes and spends the revenue on a range of economic activities. I constrain the Government to maintain a constant budget balance. This implies that 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 follows:[12]

$$\overline{GOVBAL_t} = GY_t - GEXP_t \tag{4.5}$$

In (4.5) $GOVBAL$ is the government's budget which is equal to the difference between government's revenues from different sources, GY, and government's spending $GEXP$. In the base year $GOVBAL$ is negative,

[12]This is a simplified version of equation A.40 in the Appendix A.

indicating a fiscal deficit that I assume to be fixed in the present analysis.

I 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, I explore other cases, including where the Government fixes its expenditure and adjusts the income tax rate.

4.4.5 Dataset, income disaggregation and energy use

I calibrate the UK-ENVI CGE model on the UK Social Accounting Matrix for 2010.[13] The data has 30 different productive sectors,[14] including 4 main energy supply industries that encompass the supply of coal, refined oil, gas and electricity. The SAM identifies UK households, the UK Government, imports, exports and transfers to and from the rest of the World (ROW).

Table 4.1: 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 E), I use a version of the SAM in which the household sector is disaggregated into 5 household income quintiles (HG), according to the UK Living Costs and Food Survey. The income bands are described and related to weekly gross incomes in

[13]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/

[14]See Appendix C for the full list of sectors and the corresponding sectors in the 2010 IO table.

Table 4.1.

Table 4.2 shows residential energy spending (on electricity, gas and coal) for each household as percentage of total energy consumption and of total consumption spending.

Table 4.2: Percentage of energy used for domestic purposes in total energy consumption and in total consumption

	HG1	HG2	HG3	HG4	HG5
Res. energy /Tot. energy	89.6%	85.2%	81.4%	76.2%	69.9%
Res. energy /Tot. cons.	6.7%	5.5%	4.5%	3.8%	2.6%

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.

4.5 Simulation scenarios

As explained above (Section 4.3), 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, I focus on specifying and explaining simple and transparent scenarios, rather than attempting to detail and conduct simulations of particular policy options. I 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 I assume that the energy efficiency improvement occurs in all households, regardless of their income; then,

b, where I 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** I 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. (2014a), 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** I consider in broad terms different options for how Government may fund the increase in energy efficiency. Given that I do not have information about the likely cost of increasing household energy efficiency by 10% in UK, I 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 this difference in the expenditure items of its own budget, as shown below.

(4.6)

$$\overline{GOVBAL_t} = GY_t - GEXP_t + \Delta EC_t \tag{4.6}$$

In order to keep the budget balanced when ΔEC[15] is negative, the Government can either reduce its current expenditure, GEXP, or increase its income, GY. In the sixth period (year) after the efficiency improvement, I consider that it has been completely paid for and Equation (4.6)

[15]Recall that EC is household consumption of residential energy use as defined in Equation eq2:ces

is replaced by its standard version described in (4.6).[16]

Following this approach, in Scenario 2 I 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.

In Scenario 3 I assume that a 10% household energy efficiency improvement is funded through a temporary rise in the income tax rate. 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.

[16]Again, I 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 the long-run results below.

4.6 Results

4.6.1 Costless improvement in household energy efficiency

Table 4.3 shows the short-run (SR) and long-run (LR) 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).

I 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 I 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 4.3 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

Table 4.3: % change in key macroeconomic variables from a 10% costless household residential energy efficiency increase

	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
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

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[17] 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 4.3, 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%).

The third and fourth columns of Table 4.3 show the corresponding results when I limit the increase in energy efficiency to the lowest in-

[17] See Appendix D for a brief discussion of the rebound effect and details on its calculation.

come 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%). 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 4.3.

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

Indeed if we refer to the long-run results for the change in household disposable income net of savings (i.e. consumption spending) in Table 4.4, 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 4.3 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.

Table 4.4: % change in households income and energy expenditure in Scenarios 1a and 1b

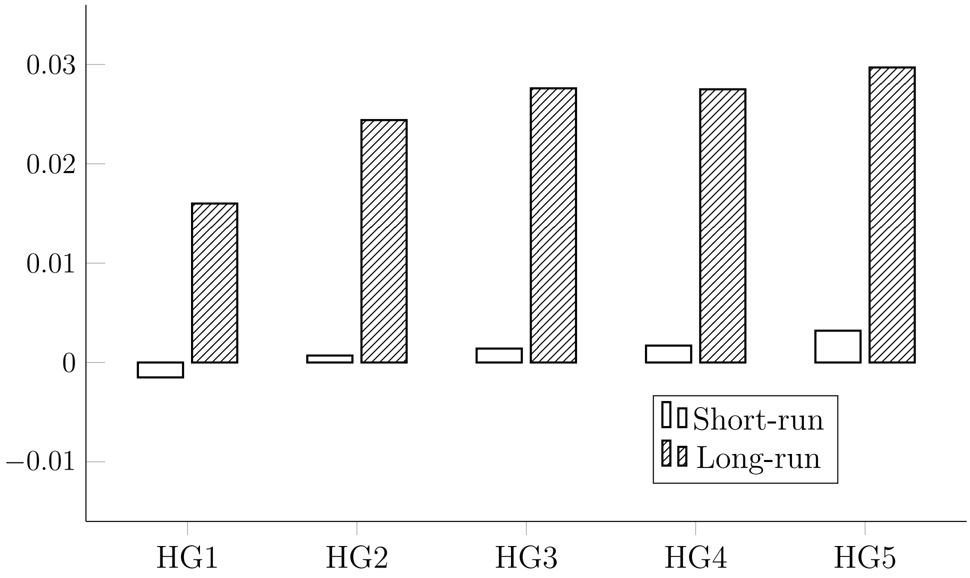
	HG1		HG2		HG3		HG4		HG5	
	SR	**LR**	**SR**	**LR**	**SR**	**LR**	**SR**	**LR**	**SR**	**LR**
a. Scenario 1a.										
Disposable income (excl. savings)	0.70	0.70	0.60	0.63	0.54	0.60	0.51	0.60	0.43	0.52
Residential energy	-1.99	-2.31	-2.19	-2.49	-2.34	-2.61	-2.44	-2.68	-2.61	-2.86
Share of income spent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

Comparison of the results in Scenarios 1a and 1b reported in Table 4.4 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 4.3 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.

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 I have not given any consideration to how increased energy efficiency may be funded. Therefore, in the next section, I report on extended simulations where I incorporate a basic consideration of the impacts of applying some treatment of cost via the public budget.

For completeness, I have run alternative simulations where the other income quintiles are in turn each the recipients of the energy efficiency increase. As we can see from Figure 4.3, where I plot the short-run and long-run percentage change in GDP for each quintile, in all the other cases the positive stimulus from their boosted and reallocated spending is sufficient to generate a positive expansion from the first period. Moreover, the long-run impact is normally greater the higher is the initial income level in the household in question.

Figure 4.3: Short-run and long-run percentage change GDP income from a 10% household energy efficiency increase in each household group



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

Funding energy efficiency improvements via a temporary reallocation of current public spending

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, in the manner detailed above in Section 4.5 (Scenarios 2a and 2b). Results for these Scenarios are reported in

Table 4.5.

Table 4.5: % change in key macroeconomic variables from a 10% household residential energy efficiency increase funded via reallocation of current Government expenditure

	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
Total energy consumption	-1.83	-1.87	-0.24	-0.24
Residential energy consumption	-2.51	-2.62	-0.32	-0.33
Household rebound in res. 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

The main impact of the required reduction in Government spending in other areas of the economy (by 0.86%) is a short-run contraction in economic activity. This is exacerbated by the contraction in energy sectors due to the lower energy demand and the crowding out of exports caused by price rises. For this reason, GDP decreases in the short-run by -0.02%.

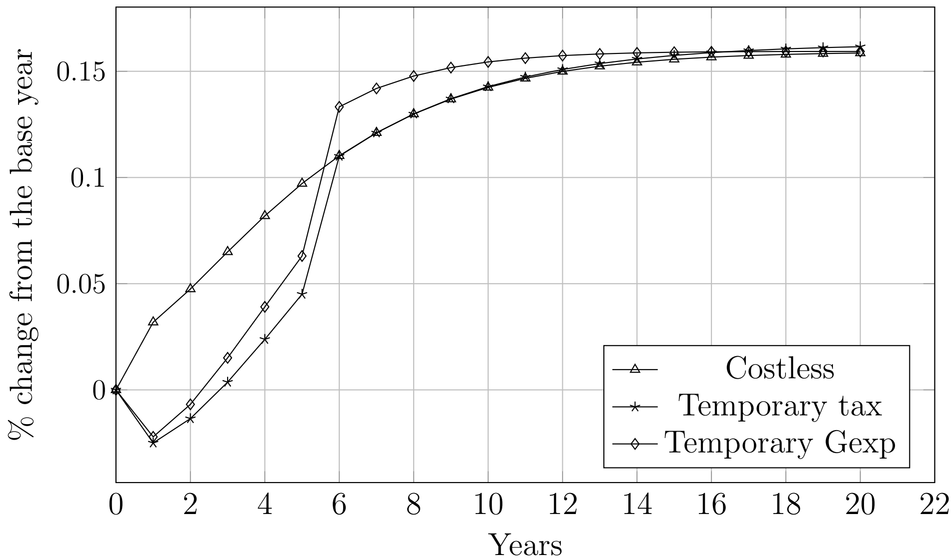
Investment falls in the short-run in the energy sectors, and also in the public administration sector. However, it increases in the other sectors, so that net total investment is still increases. This is for two main reasons: first some sectors are unaffected by the reduction in government spending simply because the spending on these sectors is zero in the base year; second because investors have forward-looking expectations, which means that they adjust their decisions taking into account for the fact that government spending will rise again in five years.

The contraction in activity actually continues for less than the assumed 5-year period of required reallocation of government expenditure. Again, this is because firms are forward looking, that is, 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 (-0-01% in HG2&3 and -0.02% in HG4&5).

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. As Figures 4.4 and 4.5 show, following an initial drop, GDP starts to rise such that in period 5, a year before the government spending goes back to its original level, it is above its baseline value. In the long-run, the costless and the government funded case converge on the same equilibrium.

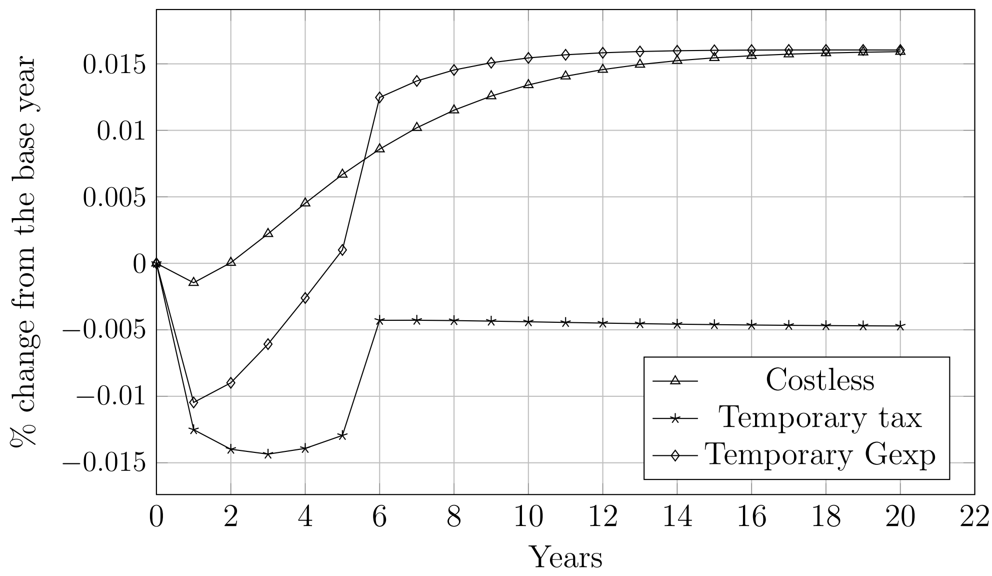
Figure 4.4: Period by period % change in GDP from a 10% residential energy efficiency increase in all households



Funding energy efficiency improvements via a temporary change in the income tax rate

When I 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, as we can see from Table 4.6. First, as noted in Section 4.5, the change in the income tax rate 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 4.4 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 4.5: Period by period % change in GDP from a 10% residential 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 4.5 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. Also, note that the endogenous income tax rate increases in the long-run (by 0.24 %) in order to maintain the government's budget balanced with fixed government spending. However, again, I 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, as I show in Figure 4.6, where I repeat the same simulation one group at the time.

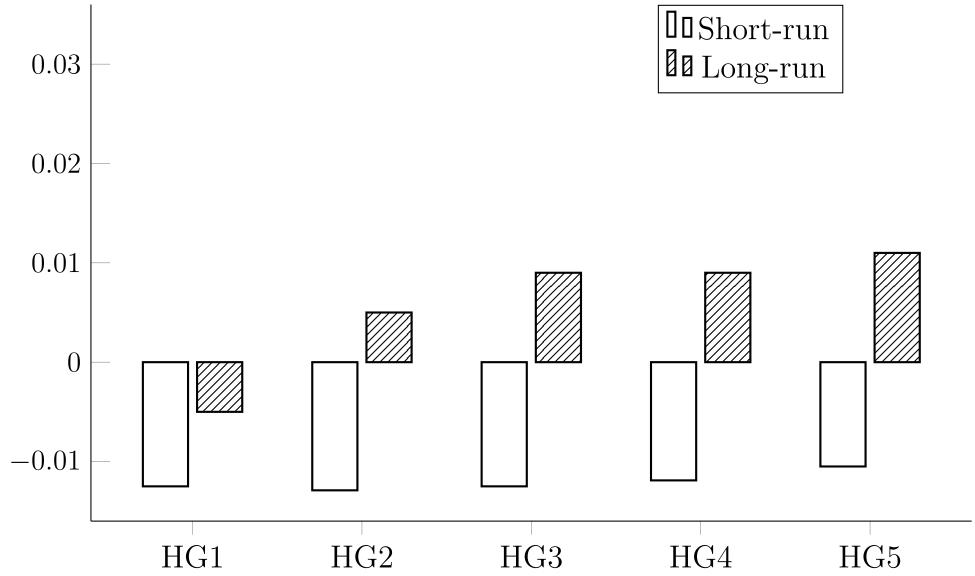
Moreover, while the impact on income used for consumption is very

Table 4.6: % change in key macroeconomic variables from a 10% household residential energy efficiency increase funded via income tax

	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	0.09	0.45	-0.04	-0.03
Import	0.29	0.58	-0.03	0.02
Export	-0.25	-0.37	0.01	-0.03
Total energy use	-0.85	-0.89	-0.13	-0.14
Disposable income (excluding savings)	0.11	0.59	-0.04	0.02
Income tax	0.97	-0.02	0.24	0.24
Total energy consumption	-2.05	-1.86	-0.31	-0.28
Residential energy consumption	-2.71	-2.61	-0.38	-0.37
Household rebound in res. 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

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 payment for efficiency is complete, 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 4.7. Note that the biggest 'loser' is the highest income

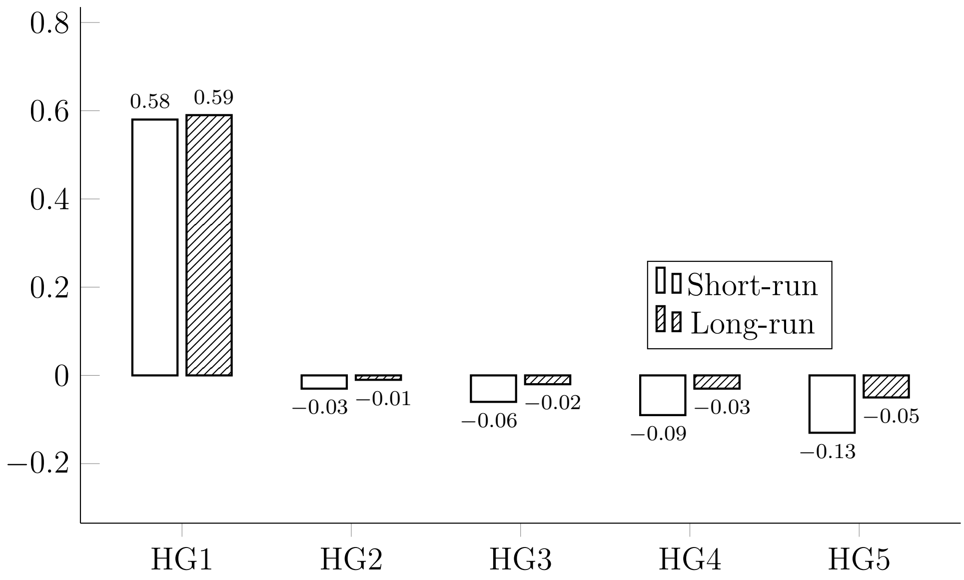
Figure 4.6: Short-run and long-run percentage change in GDP from a 10% household energy efficiency increase funded via income tax in each household group



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.

I have run a specific sensitivity scenario where I 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. I 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. I 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 4.7: 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 short term. 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.

4.7 Relaxing the assumption of a common elasticity of substitution across household income groups

As I explain in section 4.4.1, in the absence of better information I assume a common value for the elasticity of substitution across the five income groups. However, it may be argued that different household income groups have different tastes in consumption, which suggests that these values could potentially be different. For example, we could imagine that lower income household groups would be more attracted by a reduction in the price of energy, especially those households who have been under heating their homes. For this reason, they could be associated with a higher elasticity of substitution. Similarly, we may argue that high income households are already close to their satiation point in energy consumption, and that they would prefer to shift their consumption towards other goods and services.[18]

To reflect this scenario I impose a higher elasticity of substitution the first group, 0.7, and I impose increasingly lower values for higher income groups so that group 2 has and elasticity of substitution of 0.6, groups 3 4 and 5 have an elasticity of respectively 0.5, 0.4 and 0.3. I repeat the simulations of Scenario 1, by increasing energy efficiency in household residential energy consumption by 10% in all household groups simultaneously. I then repeat the same efficiency improvement but applying it to each group in turn rather than simultaneously.

[18]This is consistent with the UK findings in Chitnis et al. (2014) where lower income households are more price elastic in energy use than higher income households.

Table 4.7: % change in households income and energy expenditure from a costless 10% residential energy efficiency improvement in all household simultaneously and group by group

	HG1		**HG2**		**HG3**		**HG4**		**HG5**	
	$\varepsilon = 0.7$		$\varepsilon = 0.6$		$\varepsilon = 0.5$		$\varepsilon = 0.4$		$\varepsilon = 0.3$	
	SR	**LR**	**SR**	**LR**	**SR**	**LR**	**SR**	**LR**	**SR**	**LR**
a. All groups										
Disposable income (excl. savings)	0.72	0.71	0.61	0.63	0.54	0.60	0.51	0.60	0.44	0.52
Residential energy	-0.93	-1.45	-2.16	-2.58	-3.32	-3.64	-4.42	-4.62	-5.57	-5.71
Share of income spent on res. energy	-1.63	-2.15	-2.75	-3.19	-3.84	-4.21	-4.90	-5.19	-5.98	-6.20
Rebound in residential energy	90.75	85.46	78.39	74.19	66.79	63.63	55.82	53.77	44.26	42.86
b. Group by group										
Disposable income (excl. savings)	0.60	0.61	0.50	0.51	0.41	0.42	0.35	0.37	0.26	0.28
Residential energy	-1.58	-1.61	-2.69	-2.74	-3.77	-3.83	-4.82	-4.87	-5.91	-5.96
Share of income spent on res. energy	-2.17	-2.20	-3.17	-3.23	-4.17	-4.24	-5.15	-5.22	-6.15	-6.22
Rebound in residential energy	84.24	83.92	73.11	72.56	62.30	61.67	51.81	51.25	40.93	40.36

As Table 4.7 shows, the elasticity of substitution impacts the extent to which the energy efficiency improvement can reduce residential energy use. HG1 decreases its residential energy use by 0.9% in the short-run and 1.45% in the long-run which is less than what I find in Section 4.6. HG2 is virtually unchanged as the elasticity value almost the same as Scenario 1, while groups 3, 4, and 5 reduce their residential energy use by more. If we focus on Group 1, the share of income spent on residential energy decreases by less than in Scenario 1. Intuitively, people in this group are more willing to substitute their consumption in favour of energy when it becomes relatively cheaper. However, disposable income increases by 0.7% which is in line with what I find in Scenario 1. This implies that the lowest income group is gaining in terms of additional income and decides to spend even more on residential energy, even though they can also afford to increase their spending on other non-energy goods.

The macroeconomic impact is broadly in line with the one from Scenario 1, with a small increase in GDP of approximately 0.16%. However, because in this case higher income households are associated with lower rebound, the net total reduction in residential energy use across all the groups is greater than in Scenario 1. For this reason, the total household rebound (not reported in the Tables) is more than 10 percentage points smaller than Scenario 1, 64.6%, and the economy wide rebound is 39.4%. This implies that in the above case, improving energy efficiency across all the households groups would be more effective in terms of overall reduction in final energy demand and consequent CO2 emissions, delivering at the same time the same GDP boost, and helping poorer households to increase their energy use and properly heat and light their homes.

4.8 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, I have focused my attention on how the economic expansion may provide a justification for public/government support of energy efficiency programmes.

Specifically, I have used an illustrative CGE modelling analysis for the UK to consider the general effects of government support of domestic energy efficiency programmes. I 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 I 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, my 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). Results from this paper 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 a justification for support.

However, my findings suggest that the means of providing support for energy efficiency programmes should be carefully considered and examined. My 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, I reserve fuller consideration of specific funding mechanisms for future research, ideally in consultation with policy decision makers particularly within the UK.

Chapter 5

Can a reduction in fuel use result from an endogenous technical progress in motor vehicles? A partial and general equilibrium analysis.

5.1 Introduction

Gordon (2016) stresses that technical progress in household consumer services has been a major, typically underestimated, element in the improvement in the standard of living in the US since 1870. In the case of energy savings technical improvements, the IEA (2014) emphasises that this could deliver a wide range of economic benefits, linked to the more efficient use of resources. This is also supported by the economy-wide literature on energy efficiency (Broberg et al., 2015; Duarte et al., 2016; Lecca et al., 2014a; Turner, 2013; Yu et al., 2015).

However, Gillingham et al. (2016) argues that energy efficiency improvements could be linked to changes in characteristics of energy using technologies. These technologies combined with physical energy produce energy intensive services, such as using a lighter motor vehicle to increase the output of miles travelled. This suggests that we should think about the consumption of energy-intensive services in which physical energy is only one of the input. These services can be thought of as self-produced and consumed directly by households (Becker, 1965).

Following Gillingham et al. (2016), I apply this conceptual approach to the provision of energy-intensive services in household consumption, such as domestic space heating and light. I operationalise this using the specific example of private transport, as being produced using refined fuel and motor vehicles. I am particularly interested in the way in which improvements in the efficiency of vehicles and fuel affect the implicit price and quantity consumed of private transport and the subsequent derived demand for fuel and vehicles. More especially, I wish to investigate the way in which an increase in the efficiency of vehicles affects the consumption of fuel. This is highly relevant in the context of policy initiatives to reduce energy use and associated carbon emissions whilst maintaining, or stimulating, economic development.

In economics, the standard definition of an energy efficiency improvement is an intervention whereby the same level of output can be obtained using less physical energy, holding all the other inputs constant. However, the introduction of an energy efficiency improvement does not imply that the output or the use of other inputs will remain constant. For example, in the case of this paper an improvement in fuel efficiency would imply that the same level of private transport could now be provided with a given vehicle and less fuel, but it also means that the price of fuel, in efficiency units, falls. Given that it is generally possible to substitute between inputs in the production of these services, improving energy efficiency typically leads to lower energy savings than expected via a rebound effect; in extreme cases, an increase in the use of energy (or backfire) can result (Khazzoom, 1980, 1987; Saunders, 2000). In this paper I investigate whether substitution possibilities imply that fuel savings can be obtained in the provision of private transport as a result of technical improvements in vehicles. That is to say, I focus on the question of whether a reduction in energy use could result as an endogenous response to efficiency improvements in the other input.

I analyse this initially using a partial equilibrium model. A simple relationship is adopted between vehicle and fuel use in the production of private transport, and between private transport and all other goods in the determination of the household consumption vector. This analysis holds household income and the prices of all inputs and other consumption goods constant. The approach is then extended through simulation using a Computable General Equilibrium (CGE) model, parameterised on UK data. This framework allows the incorporation of endogenous changes in nominal income, market prices and supply responses. Efficiency improvements in household consumption will affect the implicit price of the corresponding household service. However, these prices are not normally used in the standard calculation of the consumer price index (*cpi*), leading to potential underestimations of the economy-wide impact of household efficiency improvements (Gordon, 2016). In a final set of simulations, I recalculate the *cpi* using the endogenous price changes for private transport services. This reduction in the *cpi* has implications for the determination of the real wage and produces additional positive competitiveness effects.

The reminder of the paper is organised as follows. Section 5.2 reviews the current literature on energy efficiency in the context of modelling the household consumption of energy-intensive services. Section 5.3 outlines the partial equilibrium analysis. Section 5.4 describes the CGE model and Section 5.5 the various simulation set ups. The simulation results are reported in Section 5.6 and further discussed in Section 5.7. Section 5.8 is a short conclusion.

5.2 Background

Many studies have analysed the impact of energy-saving technical improvements in consumption in order to assess the potential net impact on final energy use (see for example Chitnis et al., 2014; Chitnis and Sorrell, 2015; Duarte et al., 2016; Dubin et al., 1986; Druckman et al., 2011; Frondel et al., 2008, 2012; Lecca et al., 2014a; Lin and Zeng, 2013; Schwarz and Taylor, 1995; West, 2004). A common characteristic of this literature is that physical energy is modelled as if it were consumed directly. Increased energy efficiency is normally found to reduce final energy use but with some rebound effect. The size of this rebound varies across the studies, partly depending on the modelling approach. Some of this work relates energy efficiency improvements to the capital costs associated with the increase in efficiency (Chitnis and Sorrell, 2015; Mizobuchi, 2008; Sorrell and Dimitropoulos, 2008). However, in making the rebound calculation none explores the relationship between the physical energy and the capital appliances used in the production of the energy-intensive consumer services.

There are three papers that specifically attempt to model energy-intensive consumer services as composite goods combining physical energy and technology. Walker and Wirl (1993) model the demand for private transport as a service obtained by a combination of fuels and technology. This technology converts fuel use into miles travelled. In this approach, where the consumer allocates all her budget to private transport services, the marginal utility of consumption is given by price of the energy-intensive service. This price is calculated as the price of fuel divided by the efficiency of vehicles. If this efficiency increases, the price of the energy-intensive service decreases, stimulating a rise in the quantity demanded. Haas et al. (2008) adopt the same method but focus on residential energy use. They find that technical progress has the effect of reducing the price of residential energy services, leading to significant increases in the demand for these services and the derived demand for physical energy, producing a direct rebound effect.

Hunt and Ryan (2015) extend Walker and Wirl (1993) and develop a model of household consumption by separately identifying several energy-intensive services (heating, lighting, motoring, etc.), each formed as a combination of physical energy and technology. These services, together with all other consumption goods, are elements of total household expenditure. Hunt and Ryan (2015) asserts that models that do not consider consumer energy demand in the context of providing a service are misspecified and are likely to produce biased estimation of key behavioural parameters, such as the price and income elasticities of energy demand. The paper demonstrates this point by using UK data to econometrically estimate two models. One is the standard model where energy is included on the same footing as any other good or service. The second is a model augmented with technology that converts energy into energy services. The results show that the income and price elasticities of energy demand are quite different in the two models. In particular, when technology is introduced in the model, its coefficient is statistically significant, indicating that the augmented specification is preferred.

In an attempt to consolidate this literature, Gillingham et al. (2016) argues that producing vehicles using a lighter material would improve fuel efficiency of motoring services and increase the number of miles travelled per unit of fuel. This implies that the price of the energy service would depend on both the price of energy and the price of the product that deliver the service. Although it does not discuss specifically how to model such energy intensive services, and is mostly interested in the implications of energy efficiency for the calculation of the rebound effect, Gillingham et al. (2016) offer an interesting starting point. In this paper I operationalise this approach, starting with a partial equilibrium analysis and them moving to a Computable General Equilibrium approach.

5.3 Modelling household production of motoring services

5.3.1 The basic model

Initially, suppose that a consumer allocates a given nominal budget to private transport and that market prices are fixed, so that the analysis takes a partial equilibrium form. The output of the energy-intensive private transport service is here given by miles travelled, m, which is produced by households through a combination of motor vehicles, v^e, and refined fuel (petrol and diesel),f^e. It is convenient to express these inputs in terms of efficiency units, indicated by the e superscript. However, it should be noted that in the present analysis, the efficiency of fuels often does not change, so that for the fuel input, efficiency and natural inputs are typically identical. The household production function for private transport is therefore given as:

$$m = m(v^e, f^e) \tag{5.1}$$

The consumer will choose the combination of vehicles and fuel that maximises the amount of miles travelled, m, given her budget constraint.

Suppose that the production of private transport becomes more efficient due to technical progress.[1] To investigate the implications of such improvement I employ a graphical analysis in which motor vehicles and refined fuels are represented in efficiency units. I specify the relation between natural and efficiency units in the household utility maximisation problem as follows:

$$\begin{aligned}
&\max m = m(v^e, f^e) \\
&subject\ to \\
&p_f^n f^n + p_v^n v^n - y \geq 0 \\
&where \\
&z^e = \varepsilon^z z^n \text{ and} \\
&p_z^e = \frac{p_z^n}{\varepsilon_z} \text{ for } z = (f, v)
\end{aligned} \tag{5.2}$$

In (5.2) p indicates a price, ε is an efficiency parameter, e is a subscript for efficiency units and n for natural units. From maximisation we have that:

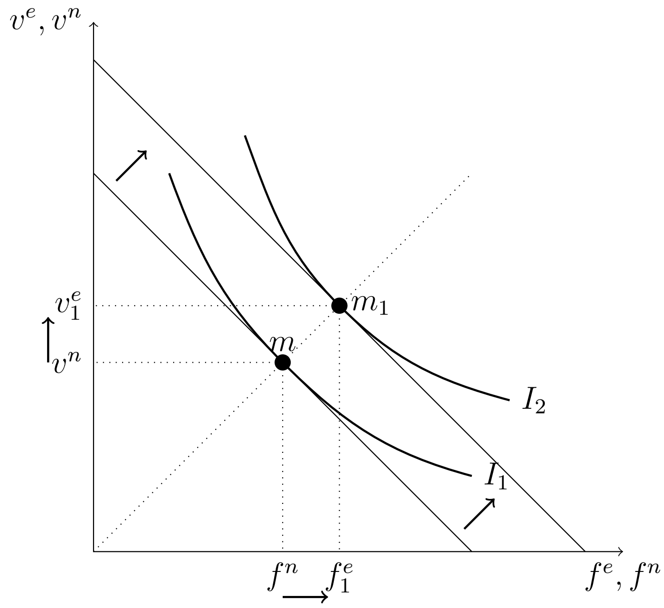
$$\begin{aligned}
&\frac{\partial m}{\partial z^n} = p_z^n = \frac{\partial m}{\partial z^e}\varepsilon_z \\
&\frac{\partial m}{\partial z^e} = p_z^e = \frac{p_z^n}{\varepsilon_z}
\end{aligned} \tag{5.3}$$

Expression (5.3) implies that for any input whose efficiency is increased, technical progress is reflected in a change in its price, expressed in efficiency units. Technical changes can therefore be represented through adjustments in the budget constraint, specified in efficiency units.

[1] There are three primary benchmark cases: a) motor vehicles and fuels become equally more efficient; b) only motor vehicles become more efficient; c) fuels become more efficient. However, hybrid cases are also possible where both inputs become more efficiency but at different rates.

To illustrate this approach let us start with a simple symmetric technical improvement in both inputs. I parametrise the model so that f, v and m are unity, and in absence of efficiency changes, quantities in natural and efficiency units are identical.

Figure 5.1: Technical progress in motor vehicles and fuels



In Figure 5.1 the horizontal axis represents fuels both in natural and efficiency units, while the vertical axis represents vehicles in natural and efficiency units. The technical improvement is represented by a parallel shift in the budget constraint expressed in efficiency units. The consumer can now choose a higher isoquant and increase her production of private transport from m to m_1.[2] In the simple case of a linear homogeneous domestic production function, the outcomes will lie on a straight line through the origin. The new level of private transport is given by the combination of motor vehicles and fuel, v_1^e and f_1^e, both measured in

[2]The points m and m_1 are where the relevant budget constraints are tangent with the highest relevant isoquant.

efficiency units. However, in natural units the expenditure on v_n and f_n is unchanged, though the consumer can now produce more travelled miles from the same nominal budget.

Let us now consider the case where only one input becomes more efficient, specifically motor vehicles. This represents vehicle-augmenting technical progress, which is the focus of this paper. However, the fuel augmenting technical change case would be identical but opposite to the vehicle augmenting case. In this case the technical improvement decreases the price of vehicles in efficiency units, while the price of fuel is unchanged. The impact of the reduction in the price of vehicles on the consumption of fuel depends on the elasticity of substitution between the two inputs:

$$\sigma_{v,f} = \frac{-\partial(f^e/v^e)(MRS_{f^e,v^e})}{\partial(MRS_{f^e,v^e})(f^e/v^e)} \tag{5.4}$$

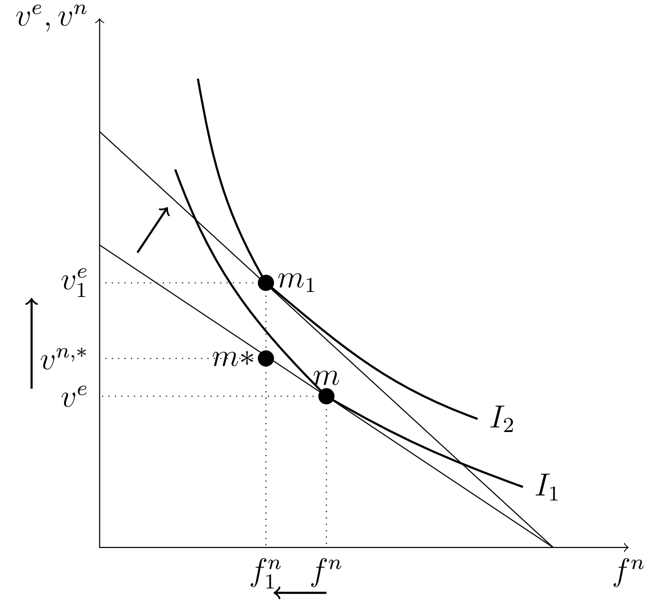
where MRS is the marginal rate of substitution between vehicles and fuel, and relates to the slope of the isoquant.[3] When $\sigma_{v,f}$ is greater than 1, the two goods are competitors. This implies that a reduction in the price of vehicles, in efficiency units, leads to a reduction in expenditure on fuel and therefore fuel use, as the consumer substitutes heavily towards vehicles. On the other hand, when $\sigma_{v,f}$ is smaller than 1, the two inputs are complements.[4] Here, with a fixed nominal budget and fixed natural input prices, as the efficiency price of vehicles falls, the corresponding

[3]The fixed elasticity of substitution measures the proportionate, not absolute, changes in each input required to maintain a constant output.

[4]An elasticity of substitution of zero implies that the two goods are perfect complements. This is where the inputs have to be used in fixed proportions and is the Leontief production technology case.

increase in consumption of vehicles is insufficient for expenditure on vehicles to increase. Therefore, in this case, following the increase in vehicle efficiency the expenditure on fuel will rise and the use of both inputs vehicles measured in efficiency units and fuel in natural units - will rise. For these reasons, the effectiveness of the technical change in reducing fuel use per unit of output is determined endogenously and depends on the substitutability between the two inputs.

Figure 5.2: Technical progress in motor vehicles



In Figure 5.2 I show the case where vehicles and fuel are competitive. Initially the consumer is at point m on the isoquant I_1. The technical improvement in motor vehicles pivots the budget constraint, expressed in efficiency units, clockwise, as the price of vehicle in efficiency units decreases. At point m_1 the consumer chooses the combination of f_1^n and v_1^e that maximises the output of private transport. This is where the new budget constraint is tangent to the highest attainable isoquant, I_2.[5] If we project m_1 onto the initial budget constraint expressed in natural units, we see that private transport output m_1 is produced at $m*$ using f_1^n , and $v^{n,*}$ inputs, both measured in natural units. The vehicle-saving technical change will always reduce fuel use per unit of output but not necessarily per £1 spent on motoring. In Figure 5.2 I have assumed that the two goods are competitive. In this case, the efficiency improvement in vehicles reduces the quantity of fuels necessary to deliver the increase in private transport services, while the use of vehicles, measured in natural units, increases. Clearly for energy-intensive household services in general, technical improvements in the non-energy inputs generate endogenous changes in fuel use which can be positive or negative.

5.3.2 Incorporating the consumption of multiple goods

So far I have assumed that the consumer has a nominal fixed budget to be spent on private transport. However, consumers allocate their income on a number of different goods and services, only one of which is private transport. Consider now a household allocating its total household budget between private transport and a composite that comprises all the other goods, a. Also assume that private transport is still a combination of vehicles and fuel. The consumption choice can then be represented by following nested function:

$$c = c(a, m(v^e, f^e)) \tag{5.5}$$

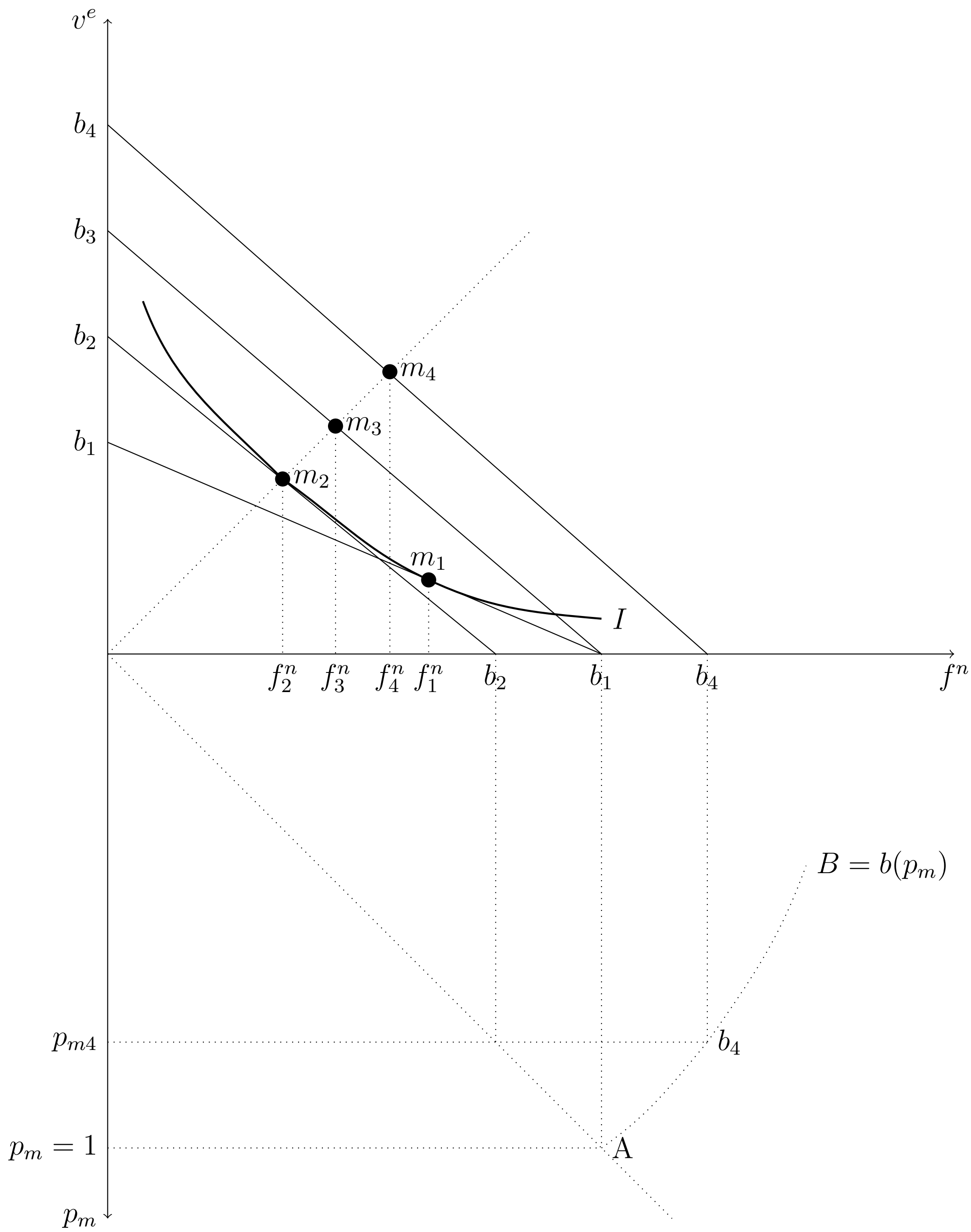
[5] For convenience, because the efficiency of fuel does not change I measure the use of fuel in natural units.

In this case, the consumption of fuel depends partly on the degree of substitution between private transport and all the other goods, $\sigma_{m,a}$. Figure 5.3 presents a graphical analysis similar to that shown in Figure 5.2. The top panel has vehicles in efficiency units on the vertical axis and refined fuel on the horizontal axis, in natural units. In the bottom panel the price of motoring p_m is on the downward-pointing vertical axis.

I parametrise the model so that the initial quantity, price, and therefore the total budget for private transport (m, p_m and b) are all unity. The consumer initially produces m_1 private transport using f_1^n fuels and some quantity of motor vehicles. With a fixed nominal budget, technical progress in motor vehicles has the effect of pivoting the budget line (in efficiency units) from b_1b_1 to b_1b_3. This replicates Figure 5.2 and implies that a constant budged can now produce more private transport because the increased efficiency of vehicles reduces the price of private transport. At this point, if we move the new budget line parallel downwards until it is just tangent to the initial (unit) isoquant, we identify the cost-minimising way for the household to produce one physical unit of private transport. Here I am essentially using the budget constraint as an iso-cost curve. The unit cost-minimising point is m_2.

The lower panel of the diagram can also be used to show the new price of private transport. This is given by point b_2 as measured along the fuel axis, because the price of fuel remains constant. Because b_1 is calibrated initially as unity, b_2 is the new price of motoring, which is now less than 1. If the demand for private transport is price elastic, as its price falls total private transport expenditure will rise. Similarly if private transport is price inelastic, with the price reduction total expenditure on private

Figure 5.3: Technical change in motor vehicles with non-fixed budget



transport will fall. In Figure 5.3, I illustrate the case where the elasticity of substitution between motoring and all other goods and services ($\sigma_{m,a}$) is greater than 1 and hence motoring is price elastic.

In the lower part of the diagram, the 45 degree line through the origin simply transfers the private transport price, given by the point where the minimum unit isocost curve hits the fuel axis (here b_2) onto the vertical axis. The B curve then gives the total motoring expenditure associated with this motoring price. Where this is expenditure figure is translated to the horizontal axis, it gives the point where the new budget constraint line cuts the fuel axis. In this case I am assuming motoring consumption is elastic, so expenditure rises (> 1). The new budget constraint is $b_4 b_4$. The point that maximises the private transport output is at m_4 with an input of fuels of f_4^n. If the private transport production function, as represented in Equation (5.5), is linear homogeneous, m_2, m_3 and m_4 will all lie on a straight line through the origin, each having the same fuel/vehicle ratio. Also the ratios of the distance from the origin indicates the change, so that in this case output increases by $0m_4/0m_2$.

If the private transport price elasticity of demand has unitary elasticity, the B curve is vertical and passes through $b_1(f^n = 1)$ and also $A(1, 1)$. For unitary elasticity, the total expenditure on private transport remains constant and the new budget constraint is $b_1 b_3$. If the demand for private transport were price inelastic, the B curve would still go through point A but would slope in the opposite direction to the curve shown in Figure 5.3. Total expenditure on private transport would fall as efficiency increases.

In Figure 5.3 energy use decreases from f_1^n to f_4^n following technical progress in vehicles. However, while in Figure 5.2 the only condition for a reduction in fuel use is to have an elasticity of substitution between refined fuels and vehicles greater than 1, here we need to account also for the substitutability between private transport and all other goods. It transpires that in the partial equilibrium setting, whether fuel use rises or falls in response to an increase in vehicle efficiency depends solely on the values of the $\sigma_{v,f}$ and $\sigma_{m,a}$.

From what we already know, we can deduce ranges of values where we can unambiguously sign the change in fuel use. When $\sigma_{v,f} > 1$ and $\sigma_{m,a} < 1$ both expenditure on private transport and the share of fuel in private transport expenditure fall. There is therefore a clear reduction in fuel consumption in this case. Using an analogous argument, if $\sigma_{v,f} < 1$ and $\sigma_{m,a} > 1$ fuel use unambiguously increase. However, when the two elasticities of substitution are both positive, a reduction in fuel use will occur only if the increase in motoring expenditure is not sufficiently large to offset the reduction in the share of fuel in private transport expenditure. Similarly, where both elasticities are negative, fuel consumption will fall only if the reduction in expenditure on private transport is sufficiently large to offset a rise in fuel expenditure as a share of total expenditure on private transport.

Holden and Swales (1993) undertake partial equilibrium analysis in a more conventional industrial production setting where output is produced with capital and labour and sold in a perfectly competitive product market. The paper derives an expression for the cross price elasticity of one input with respect to a change in the price of a second input.[6] A key result is that a reduction in the price of one input leads to an increase in the use of the second input where the price elasticity of demand for the output is greater than the elasticity of substitution between the

[6]Holden and Swales (1993) analyse the impact of labour subsidies on capital use.

two inputs. This result translates directly to the household production of energy-intensive services in general and to private transport in particular. In a partial equilibrium setting, if $\sigma_{v,f} > \sigma_{m,a}$ the negative substitution effect dominates the output effect, and as vehicles become more efficient, and their efficiency price falls, fuel use will also fall. On the other hand, if $\sigma_{v,f} < \sigma_{m,a}$, fuel use increases accompany any efficiency improvements in vehicles.

A third issue is linked to the calculation of the *cpi*. Gordon (2016) argues that efficiency improvements in household services, especially energy-intensive services such as domestic lighting, heating and air conditioning, are a significant source of bias in the calculation of the consumer price index. This, in turn, has led to an underestimation of the US growth of real GDP in the past. However, in the American figures, private transport has been treated as a special case and improvements in both fuel and vehicle efficiency have been incorporated in the calculation of the *cpi* and therefore also the growth of GDP. Standard CGE models would typically fail to account for the impact on the *cpi* of improvements in household efficiency. However, in the present simulations I can include the private transport price in an adjusted calculation of the consumer price index. I label this adjusted index cpi_{τ}. An efficiency increase in vehicles will reduce the price of private transport, whose impact on the cpi_{τ} will reduce the nominal wage for any given real wage. This will increase competitiveness with accompanying positive impacts on the economy.

5.4 A computable general equilibrium modelling application

I incorporate the conceptual framework developed in Section 5.3 in an analysis using the UK-ENVI Computable General Equilibrium (CGE) model. UK-ENVI is a dynamic CGE model designed for the analysis of disturbances in the energy sector of the UK economy.[7] It is used here to assess the impact of an illustrative 10% vehicle augmenting efficiency increase. In this version, the model is calibrated on a 2010 Social Accounting Matrix reporting transactions between 30 productive sectors,[8] the UK households, government, corporate sectors and the rest of the world (imports and exports). In the following sections I outline the main features of the model, focussing particularly on the structure of household consumption.

5.4.1 Consumption

I assume that in each time period, a representative household makes an aggregate consumption decision, C, determined by its disposable income, so that:

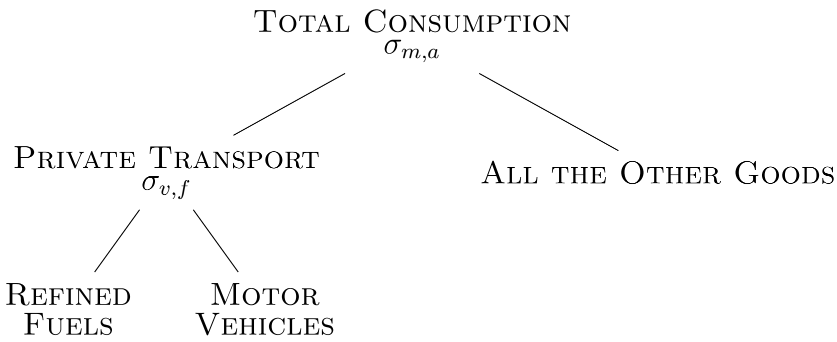
$$C_t = YNG_t - SAV_t - HTAX_t - CTAX_t \tag{5.6}$$

In equation (5.6) total consumption is a function of income YNG, savings SAV, income taxes $HTAX$, and direct taxes on consumption $CTAX$, and t indicates the time period, which is considered to be one

[7]The full mathematical presentation of the model is reported in Appendix A.
[8]Details about sector's aggregation are reported in Appendix C.

year. Total consumption is allocated to sectors through the structure described in 5.3.2. This is a nested constant elasticity of substitution (CES) function, illustrated in Figure 5.4.

Figure 5.4: The structure of consumption



This implies that household divides consumption between private transport and all other goods, where private transport is a CES combination of refined fuels and motor vehicles and 'all other goods' is a Leontief composite. Here, the central point is that in the standard UK-ENVI model there is no private transport supply sector. For this reason, I assume that households buy vehicles and fuel inputs, for which there are supply sectors, to self-produce private transport which they then directly consume. The price of private transport, albeit unobserved in the standard production accounts, can be captured through this adjustment to the consumption structure and is equal to the cost of self-production.

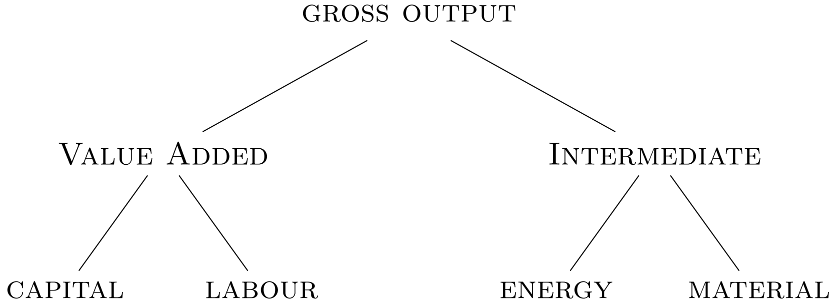
The optimal vehicle input is determined by cost-minimising private transport production. The demand function for the optimal level of vehicle expenditure is given by equation (A.102) in Appendix A. I note that motor vehicles are consumer durables and that expenditure in any period should be considered in a long-term perspective. Essentially expenditure on such items should be treated similarly to an investment in capital in conventional production sectors. For this reason I focus on long-run equilibrium results here where the desired level of vehicle expenditure, determined by the cost minimising function, equals, by definition, the actual level of motor vehicle expenditure.

Clearly, even after this adjustment, in practice consumption choices are the result of a more complicated set of consumption decisions. In particular, other energy-intensive services, such as heating and lighting, can be similarly seen as self-produced composite goods. However, to enhance tractability and to simplify the interpretation of the results, I here isolate the example of private transport and assume that the remaining consumption comprises a single composite good, leaving the extension of this framework to future research. Further, household consumption comprises goods produced in the UK and imported goods from the rest of the World and these are taken to be imperfect substitutes (Armington, 1969).

5.4.2 Production and investment

The production structure, outlined in Figure 5.5, is represented by a capital, labour, energy and material (KLEM) CES function.

Figure 5.5: The structure of production



Here labour and capital are combined to form value added, while energy and materials form a composite of intermediate inputs. In turn, the combination of intermediate and value added gives total output. Again, imported and locally produced intermediate inputs are assumed to be imperfect substitute, via an Armington link (Armington, 1969).

For simplicity I assume that investment is determined by a myopic[9] agent according to the following partial adjustment mechanism:

$$I_{i,t} = v \cdot \left[K^{\star}_{i,t} - K_{i,t}\right] + \delta \cdot K_{i,t} \tag{5.7}$$

In (5.7) investment is a function of the gap between the actual and desired capital stock, $K^{\star}_{i,t}$ and $K_{i,t}$ respectively, plus depreciation which occurs at the rate δ. The parameter v is an accelerator (Jorgenson, 1963) and represents the speed at which the capital stock adjusts to the desired level of capital. In steady state the following conditions are satisfied:

$$\begin{aligned} &K^{\star}_{i,t} = K_{i,t} \\ &\text{therefore} \\ &I_{i,t} = \delta \cdot K_{i,t} \end{aligned} \tag{5.8}$$

Equation (5.7) simply states that the desired and actual level of capital stocks are equal. From equation (5.8) this implies that in long-run equilibrium gross investment just covers depreciation.

[9]The model offers the possibility of forward-looking expectation in investment. Given that in this application I am primarily interested in long-run outcomes, the two specifications would produce identical results as the long-run equilibrium conditions are identical (Lecca et al., 2013). I therefore adopt the simpler option.

5.4.3 The labour market

Ie assume that the working population is fixed and explore two alternative labour market closure; fixed real wage and wage bargaining. The fixed-real-wage closure is motivated by the 'wage resistance hypothesis', which implies that the bargaining power of workers resists any reduction in the real wage.[10]

$$\frac{w_t}{cpi_t} = \frac{w_0}{cpi_0} \tag{5.9}$$

Equation (5.9) represents the conventional fixed real wage closure, calculated as the after tax wage w divided by the standard *cpi*. However, in this paper I argue that in calculating the *cpi*, the price of private transport, p_m, which is normally unobserved, should replace the prices of refined fuel and vehicles in an augmented *cpi*. This means that:

$$cpi_{\tau,t}(p_a, p_m(p_v, p_f)) \tag{5.10}$$

When motor-vehicle efficiency improves, the price of vehicles falls thereby reducing the price of private transport. In the absence of other prices variations, there will also be a corresponding reduction in the adjusted $cpi_{\tau,t}$. The labour market can then be closed using the adjusted fixed real wage:

$$rw_{\tau,t} = \frac{w_t}{cpi_{\tau,t}} \tag{5.11}$$

[10]As explained in the next Section, 5.5, this ensures zero variation in prices in natural units in the long-run, so that essentially we do not relax the fixed prices assumption of the partial equilibrium.

If $cpi_{\tau,t}$ falls, the nominal wage decreases and this has competitiveness effects in the economy.

In the wage bargaining closure, the real wage is determined according to the following wage curve:

$$ln\left[\frac{w_t}{cpi_t}\right] = \varphi - \epsilon ln(u_t) \quad (5.12)$$

In this equation, the bargaining power of workers, and hence the real consumption wage, is negatively related to the rate of unemployment (Blanchflower and Oswald, 2009). In (5.12), $\frac{w_t}{cpi_t}$ is the real consumption wage, φ is a parameter calibrated to the steady state, ϵ is the elasticity of wage related to the level of unemployment u and takes the value of 0.06 (Layard et al., 1991). Again, I can use the adjusted cpi, $cpi_{\tau,t}$, to calculate the real wage.

5.4.4 The Government

I assume that the Government faces a balanced budget constraint, as illustrated in equation (A.40) in Appendix A. Tax rates are held constant. Any variation in revenues driven by variations in economic activity is absorbed by adjusting Government current spending on goods and services proportionately.

5.5 Simulations

The simulations are arranged into three main Scenarios. In each Scenario I introduce a 10% efficiency improvement in motor vehicles and explore four variants. These variants exhibit different elasticities of substitution between private transport and all the other goods and between motor vehicles and refined fuels. These combinations of elasticities are given in Table 5.1. I have chosen two specific values for each of the two key elasticities, one elastic (> 1) and the other inelastic (< 1) and then run simulations for each of the four possible combinations. This extends the partial equilibrium analysis outlined in Section 5.3.2 to general equilibrium.

Table 5.1: Summary of sub-scenario simulation parameter values.

	Transport & Non Transport		Motor vehicles & Refined Fuels	
A)	Competitive	$\sigma_{m,a} = 1.5$	Competitive	$\sigma_{v,f} = 1.2$
B)	Complementary	$\sigma_{m,a} = 0.5$	Competitive	$\sigma_{v,f} = 1.2$
C)	Competitive	$\sigma_{m,a} = 1.5$	Complementary	$\sigma_{v,f} = 0.3$
D)	Complementary	$\sigma_{m,a} = 0.5$	Complementary	$\sigma_{v,f} = 0.3$

The Scenarios differ in that I impose a different wage setting process in each. In Scenario 1, I assume that the real wage is fixed and calculated using the standard consumer price index. This produces simulations where, in the long run, all the prices in natural units are unchanged. In this sense I retain one of the key assumptions of the partial equilibrium analysis, fixed prices, whilst allowing the aggregate level of economic activity to change.

In the second Scenario, I again impose a fixed real wage, but in this case calculated using the adjusted consumer price index, cpi_{τ}, as defined in equation (5.10). As anticipated, the reduction in the price of private transport caused by the increase in efficiency in motor vehicles reduces the cpi_{τ}. The nominal wage therefore falls, reflecting the fact that a lower nominal wage will maintain the constant real wage, measured using the adjusted consumer price index, cpi_τ. The reduction in the real wage increases competitiveness. In the third Scenario, I incorporate the wage bargaining function, detailed in equation (5.12), but again use the adjusted consumer price index, cpi_τ, to calculate the real wage. In this case, any aggregate stimulus to the domestic economy that generates a reduction in the unemployment rate will partly be mitigated by a reduction in competitiveness.

5.6 Simulation results

I report only long-run equilibrium results, where the conditions in equation (5.8) are satisfied. This is because I am primarily concerned with the steady-state impacts, rather than the short-term dynamics of adjustment. However, it was also the case that in earlier test simulations the short- and long-run results were in fact very similar.

5.6.1 Scenario 1: the model with fixed real wage and standard cpi

Table 5.2 has two sections. The top section reports percentage changes in the composition of household consumption; the bottom section, the impact on key macroeconomic indicators. Each column of the table represents a different simulation. For each case I report the results for particular values for the elasticity of substitution between refined fuels and motor vehicles, $\sigma_{v,f}$, and between private transport and all other goods, $\sigma_{m,a}$.

Table 5.2: Percentage change from the baseline from a 10% efficiency improvement in households motor vehicles consumption (Scenario 1)

	A	B	C	D
	$\sigma_{m,a}$=1.5	$\sigma_{m,a}$=0.5	$\sigma_{m,a}$=1.5	$\sigma_{m,a}$=0.5
	$\sigma_{v,f}$=1.2	$\sigma_{v,f}$=1.2	$\sigma_{v,f}$=0.3	$\sigma_{v,f}$=0.3
	Household consumption			
All other goods	-0.05	0.04	-0.06	0.03
Private transport	5.82	1.97	5.65	1.90
Price of transport	-3.67	-3.67	-3.58	-3.58
Motor vehicles	3.12	-0.64	-2.24	-5.71
Price of vehicles	0.00	0.00	0.00	0.00
Price of vehicles eff units	-10.00	-10.00	-10.00	-10.00
Fuels	1.18	-2.51	4.50	0.79
Price of fuel	0.00	0.00	0.00	0.00
Vehicles intensity in transport	1.16	1.16	-4.03	-4.04
Fuels intensity in transport	-0.75	-0.74	2.58	2.58
	Macroeconomic impacts			
GDP	-0.02	0.02	-0.03	0.00
cpi	0.00	0.00	0.00	0.00
Nominal wage	0.00	0.00	0.00	0.00
Real wage	—	—	—	—
Employment	-0.02	0.02	-0.04	0.00
Unemployment rate	0.29	-0.27	0.60	0.04
Investment	-0.02	0.01	-0.03	0.01
Household consumption	-0.02	0.01	-0.03	0.00
Household income	-0.01	0.01	-0.02	0.00
Exports	0.00	0.00	0.00	0.00

The macro-economic changes reported for this Scenario are very small, so that initially I focus on the micro-economic results for specific sectors. Because the income variations are slight, the qualitative results are very close to those derived in the partial equilibrium analysis from Section 5.3.2. To begin, note that in the long run there are no changes in the price of vehicles, fuel or the *cpi* in any of the simulations in this Scenario. This is as we would expect: the fixed real wage assumption, together with unvarying, exogenous interest rates and import prices, ensures that once capacity is fully adjusted, there are no endogenous changes in the market prices of goods (McGregor et al., 1996).

Because there is no change in the price of fuel or vehicles measured in natural units, in all of the simulations reported in Table 5.2 the price of vehicles, measured in efficiency units, falls by 10%, the full amount of the efficiency gain. This fall in the price of vehicles lowers the price of private transport. The change in this price varies across the simulations, reflecting the different elasticities of substitution between vehicles and fuel imposed in each case. However, this price variation is quite limited, the range being between reductions of 3.56% and 3.67%. Essentially, the differences between the outcomes in the individual simulations in this Scenario reflect how consumers react to the same reduction in the price of vehicles, in efficiency units, and the corresponding very similar across simulations - reductions in the price of private transport.

The results reported in column A are for elasticity values for which both fuel and vehicles, and private transport and other commodities are competitors. The values of $\sigma_{v,f}$ and $\sigma_{m,a}$ are 1.2 and 1.5 respectively, so that $\sigma_{v,f} < \sigma_{m,a}$. Therefore from the analysis in Section 3, we expect fuel use to rise. In this case, the price of transport falls by 3.67% which translates to a 5.82% increase demand for, and a 2.15% increase in expenditure on private transport. This output is generated by a 13.12% increase in vehicles use (in efficiency units) and 1.8% increase in fuels.

With the specific elasticity values adopted in this simulation, the change in fuel use is positive. Although the share of fuel in private transport, as measured by $\frac{p_f^n f^n}{p_m m}$ decreases by 0.75%, reflecting the high elasticity of substitution between fuel and vehicles, this is not large enough to offset the impact of the increased demand for private transport on the derived demand for fuels. There is a small, 0.05%, contraction in the consumption of all other goods.

In column B, the relatively high value of the elasticity of substitution between vehicles and fuel, $\sigma_{v,f}$, is retained, but $\sigma_{m,a}$ is reduced to 0.5, so that private transport and all other goods are now complements. Because the elasticity of substitution between vehicles and fuel has not changes, the reduction in price of private transport is as in column A. Following this reduction, the consumption of private transport increases. However, the value of $\sigma_{m,a}$ is smaller than for the simulation reported in column A, so that output of private transport rises only by 1.97% and expenditure on private transport falls by 1.70%. Vehicle consumption increases by 9.36% in efficiency units, which corresponds to a 0.64% reduction in physical units, while fuel input falls by 2.51%. In this case, consumption of all other goods slightly increases by 0.04%.

In the partial equilibrium analysis in Section 5.3.2, with the parameter values used in the simulation reported in column B we know unambiguously that refined fuels use will fall. This is because there must be a lower share of fuels in private transport production and the expenditure on private transport must also fall and there is no change in the price of fuel. If this simulation were represented in Figure 5.3, the B curve would be sloped in the opposite direction.

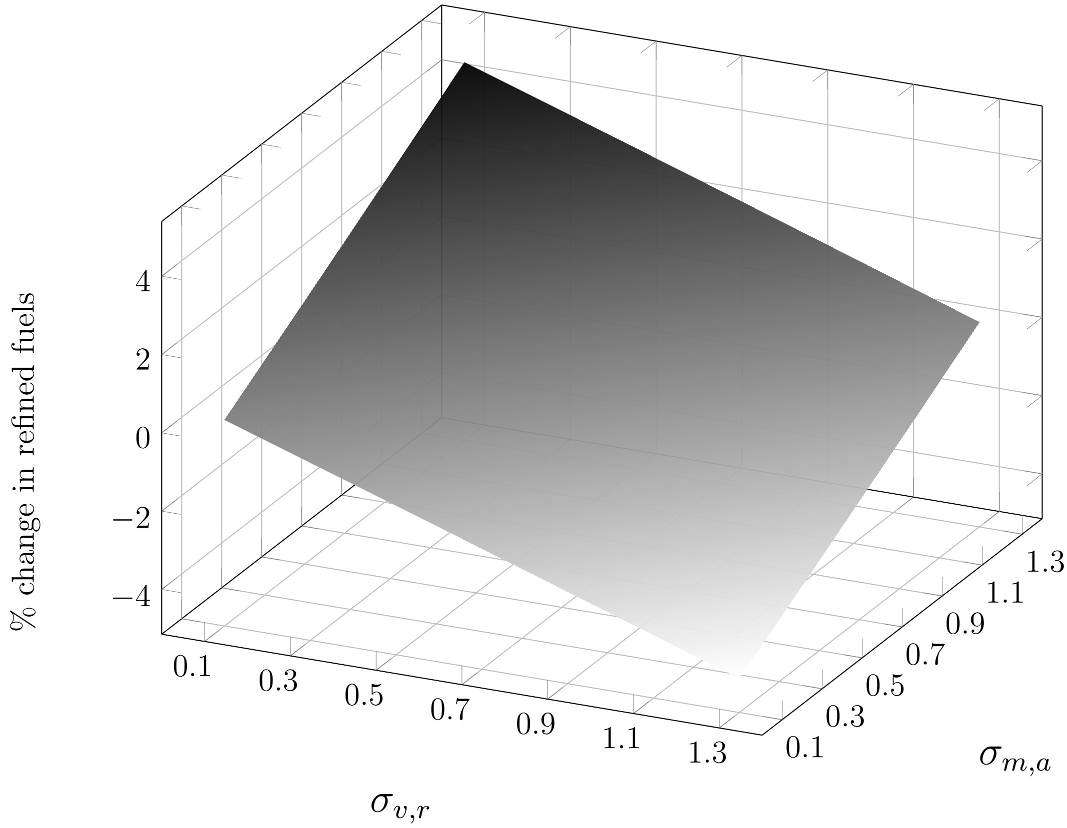
In the simulation reported in column C, $\sigma_{m,a}$ equals 1.5, as in column A, while $\sigma_{v,f}$ equals 0.3. In this simulation, private transport and all other goods are competitors, but refined fuels and motor vehicles are complements. This is another case where in the partial equilibrium analysis in Section 5.3.2 the outcome is unambiguous; fuel use will rise. The reduction in the price of private transport is here slightly less than in simulations A and B. This reflects the lower elasticity of substitution between fuel and vehicles which restricts substitution into the use of the input whose price has fallen. As a result of the price reduction, consumption of private transport increases by 5.65%. As expected, this increase in the consumption of private transport is very similar to the corresponding result in column A. In this case, the complementarity between motor vehicles and fuels means that the use of both increases. Consumption of vehicles increases by 7.76%, measured in efficiency units, and the consumption of refined fuels increases by 4.50%, measured in natural units. As in column A, the consumption of all other goods decreases, in this case by 0.06%.

Finally, for the simulation results reported in column D, I use the same value for $\sigma_{m,a}$ and $\sigma_{v,f}$ as in simulation B and C respectively. Both elasticities are less than 1 which implies that both private transport and all other goods, and refined fuels and motor vehicles are complements. But again, because $\sigma_{v,f} < \sigma_{m,a}$, we expect fuel use to rise. The 3.58% reduction in the price of private transport equals the corresponding figure in Simulation C, whilst the 1.90% increase in the output of private transport is similar, but slightly less, than the corresponding result in Simulation B. Total expenditure on private transport falls by 1.68% but the share of fuel in private transport increases. The net result is that fuel use increases by 0.79%. There is also a small increase in the consumption of all other goods of 0.03%.

To investigate in more detail the sensitivity of fuel consumption to changes in elasticity values, I conduct a sensitivity exercise where I vary in turn both $\sigma_{m,a}$ and $\sigma_{v,f}$. In these simulations these elasticity values take 0.2 increments between the values of 0.1 to 1.3 inclusive. Results are represented in Figure 5.6, where the percentage change in refined fuels is plotted for each combination of $\sigma_{m,a}$ and $\sigma_{v,f}$. The figures suggest that the percentage change in fuel consumption is positively related to the value of $\sigma_{m,a}$ and negatively related to the value of $\sigma_{v,f}$. In particular, within the accuracy of the elasticity values used here, where $\sigma_{m,a} > \sigma_{v,f}$, then fuel use increases with an increase in vehicle efficiency; where $\sigma_{v,f} > \sigma_{m,a}$, fuel use falls. These simulation results clearly support the analysis of Holden and Swales (1993).

Recall that in the discussion in Section 5.3.2, I argued that I had no prior expectation as to the direction of the macroeconomic impact of the technical progress in vehicles where the natural prices of inputs were held constant. In the long-run simulations reported in Table 5.2, the product prices (and therefore also the conventional *cpi*) do not change. This reflects the fixed real-wage labour market closure. In these circumstances, the macro-economic impact is similar to that generated by a change in consumer tastes affecting the composition of consumption. If the change in vehicle efficiency in the production of private transport leads to the household consumption vector having a higher direct, indirect and induced domestic content, then economic activity will rise: if the change in consumption choice leads to a reduction in domestic content, aggregate

Figure 5.6: Percentage change in refined fuels use from a 10% motor vehicles efficiency increase



economic activity will fall.[11]

In the simulations A and C, the consumption of all other goods falls and the consumption of fuel rises. Both simulations exhibit a decline in GDP, together with employment, investment, household income and aggregate household consumption. On the other hand, in simulation B, where the consumption of all goods increases and the consumption of fuel falls, all indicators of economic activity rise. In simulation D the consumption of both all other goods and fuel increases and this produces

[11]The model here operates as an extended SAM multiplier where exports are exogenous. The change in the consumption vector therefore changes the multiplier values. The exogenous export expenditure remains unchanged.

a neutral impact on economic activity. In this simulation the only aggregate variable that shows any change is investment which increases by 0.01%. These results are consistent with the intuitive notion that all other goods have a relatively high domestic content, whilst fuel has a relatively low one. Outcomes which shift consumption towards the former and away from the latter have a small stimulating impact on aggregate economic activity. Note that in this Scenario there is no conflict between energy reduction and economic expansion: in these simulations, where fuel use falls, output increases.

5.6.2 Scenario 2: using the adjusted *cpi* and real wage

In Scenario 1, the long-run *cpi*, conventionally measured, is unchanged from its baseline value because the real wage is fixed and no other market price is changing. However, the price of private transport falls by approximately 3.7%. This price is normally unobserved, as households self-produce this service and consume it directly without selling it in a market. It is therefore not included in the standard calculation of the *cpi*. As I argue in previous discussion, this may lead to bias in the calculation of *cpi*, as stressed by Gordon (2016). For this reason, I here calculate an adjusted consumer price index, cpi_{τ}, in which the fuel and vehicle prices are replaced by the price of private transport. I then use this adjusted consumer price index to derive an adjusted real wage, as explained in Section 5.4.3.

Table 5.3 reports the simulation results for this Scenario including the adjusted consumer price index, cpi_{τ}, and both the conventional and

Table 5.3: Percentage change from the baseline from a 10% efficiency improvement in households motor vehicles consumption with adjusted *cpi* (Scenario 2)

	A	B	C	D
	$\sigma_{m,a}$=1.5	$\sigma_{m,a}$=0.5	$\sigma_{m,a}$=1.5	$\sigma_{m,a}$=0.5
	$\sigma_{v,f}$=1.2	$\sigma_{v,f}$=1.2	$\sigma_{v,f}$=0.3	$\sigma_{v,f}$=0.3
	Household consumption			
All other goods	0.01	0.10	-0.01	0.09
Private transport	5.87	2.02	5.69	1.95
Price of transport	-3.71	-3.71	-3.61	-3.61
Motor vehicles	3.17	-0.57	-2.20	-5.66
Price of vehicles	-0.04	-0.04	-0.04	-0.04
Price of vehicles eff units	-10.04	-10.04	-10.04	-10.04
Fuels	1.21	-2.46	4.54	0.84
Price of fuel	-0.03	-0.03	-0.03	-0.03
Vehicles intensity in transport	1.17	1.17	-4.03	-4.03
Fuels intensity in transport	-0.75	-0.75	2.58	2.58
	Macroeconomic impacts			
GDP	0.10	0.15	0.09	0.13
cpi_τ	-0.10	-0.10	-0.10	-0.10
Nominal wage	-0.10	-0.10	-0.10	-0.10
Real wage	-0.05	-0.06	-0.05	-0.06
Real wage (cpi_τ deflated)	—	—	—	—
Employment	0.11	0.16	0.09	0.13
Unemployment rate	-1.80	-2.48	-1.42	-2.11
Investment	0.09	0.13	0.08	0.12
Household consumption	0.04	0.07	0.03	0.06
Household income (cpi_τ deflated)	0.10	0.13	0.08	0.11
Exports	0.09	0.09	0.09	0.09

adjusted real wage. The private transport price reduction triggers a drop in the cpi_τ. In all the simulations where the cpi_τ is used to calculate a constant adjusted real wage, both the adjusted consumer price index and the nominal wage fall by 0.10%. The conventionally calculated real wage falls between 0.05% and 0.06%.

The fall in the nominal wage has three primary impacts. First, the reduction in product prices, triggered by the fall in the cost of labour, generates competitiveness-driven expansionary effects. This is reflected in an increase in export demand, which rises in the long run by 0.09% in all the simulations in Scenario 2. Second, the lower nominal wage leads producers to substitute labour for capital in production and reduce the relative price of labour intensive commodities. This is reflected in higher employment and in a corresponding reduction in unemployment. It is important to remember that the import prices are exogenous and are therefore unchanged. This means that there will be some additional substitution of vehicles for fuel in the household production of private transport. Third, household nominal income increases as employment rises, stimulated by the substitution and output effects already identified, so that household total consumption increases in all the cases reported in Table 5.3.

In Scenario 2, in all the simulations GDP is higher, by 0.12% or 0.13% (in percentage points difference), than the comparable figure for Scenario 1. This means that there is a positive increase in GDP for all the simulations of between 0.09% and 0.15%. Further, the adjustment to the consumer price index increases the consumption of particular commodities, as compared to the results for Scenario 1. Consumption of all other goods, vehicles and fuel all rise, relative to the corresponding figures in Table 5.2, by between 0.03% and 0.07%. These changes are relatively small so as not to affect the qualitative fuel use results. However, in simulation A the sign on the change in the consumption of all other goods is affected, with the -0.05% figure in Scenario 1 replaced by 0.01% in

Scenario 2.

5.6.3 Scenario 3: introducing wage bargaining and adjusted cpi

In Scenario 2 I introduced cpi_τ but maintained a fixed real wage. This has an impact on key macroeconomic indicators, such as employment, investment and exports. The economic stimulus from the increased competitiveness delivers a boost to GDP and all the other measures of aggregate economic activity. In Scenario 3 I explore an intermediate case, where the adjusted consumer price index is used to calculate the real wage but I relax the fixed real wage assumption by imposing the wage curve from equation (5.12). The key point is that in this case, if employment increases with a fixed labour force, the accompanying fall in the unemployment rate drives an increase in the real wage. In the simulations in Scenario 3 this increase in the wage reduces some of the impact of the efficiency improvement on competitiveness.

Table 5.4 reports results for this Scenario. It is useful to compare these with the corresponding figures given in Table 5.3 for Scenario 2. Note first that the long-run adjusted real wage now increases for all the simulations as employment rises. Whilst in Table 5.3 the nominal wage across all simulations falls by 0.10%, this reduction now lies between 0.05% and 0.01%, which limits the reduction in product prices as reflected in the cpi_τ. Also, in the fixed real wage Scenario 2, exports increased by 0.09% across all simulations. With the wage curve in Scenario 3, the long-run stimulus to exports is now much lower, between 0.01% and 0.04%. Whilst all simulations in Scenario 3 register increases in GDP and the

Table 5.4: Percentage change from the baseline from a 10% efficiency improvement in households motor vehicles consumption with adjusted cpi and wage bargaining (Scenario 3)

	A	B	C	D
	$\sigma_{m,a}$=1.5	$\sigma_{m,a}$=0.5	$\sigma_{m,a}$=1.5	$\sigma_{m,a}$=0.5
	$\sigma_{v,f}$=1.2	$\sigma_{v,f}$=1.2	$\sigma_{v,f}$=0.3	$\sigma_{v,f}$=0.3
	Household consumption			
All other goods	-0.03	0.05	-0.04	0.04
Private transport	5.84	1.98	5.67	1.91
Price of transport	-3.68	-3.68	-3.59	-3.59
Motor vehicles	3.14	-0.63	-2.22	-5.70
Price of vehicles	-0.01	-0.01	-0.02	-0.01
Price of vehicles eff units	-10.01	-10.00	-10.02	-10.01
Fuels	1.19	-2.50	4.52	0.80
Price of fuel	-0.01	-0.01	-0.01	-0.01
Vehicles intensity in transport	1.17	1.16	-4.03	-4.03
Fuels intensity in transport	-0.75	-0.75	2.58	2.58
	Macroeconomic impacts			
GDP	0.02	0.04	0.02	0.03
cpi_τ	-0.08	-0.07	-0.08	-0.08
Nominal wage	-0.04	-0.01	-0.05	-0.03
Real wage	-0.02	-0.01	-0.02	-0.01
Real wage (cpi_τ deflated)	0.04	0.06	0.03	0.05
Employment	0.03	0.04	0.02	0.03
Unemployment rate	-0.43	-0.60	-0.34	-0.51
Investment	0.02	0.03	0.02	0.03
Household consumption	0.00	0.02	0.00	0.01
Household income (cpi_τ deflated)	0.07	0.09	0.06	0.08
Exports	0.03	0.01	0.04	0.02

other indicators of aggregate economic activity, these are smaller than the corresponding figures in Scenario 2. The long-run Scenario 3 impacts on the components of consumption (fuel, vehicles and all other goods) lie between the Scenario 1 and Scenario 2 values.

5.7 Discussion

The simulations report the results from modelling private transport as an energy-intensive self-produced household service. Investigating variation across the simulations produces an increased understanding of the relationship between the inputs in the production of this service. Specifically, when considering improvements in the efficiency in the production of private transport, a vehicle-saving technical improvement can lead to a reduction in fuel consumption, depending upon the values of key elasticities. However, such a reduction in both the fuel-intensity of private transport and the use of refined fuels is not brought about by an exogenous improvement in fuel efficiency. In fact, this is an endogenous reaction to an improvement in the efficiency of a good closely linked, either as a substitute or complement, in this case motor vehicles.

This shows the importance of modelling energy-intensive household services in general, and private transport in particular, as the output of a number of inputs. Moreover, in determining the overall impact of technical progress in motor vehicles on the demand for fuel, it is fundamental to take into account changes in the demand for private transport. Such changes in the quantity demanded of the energy-intensive service generate an additional increase or reduction in the derived demand for the input goods.

When the *cpi* is calculated using the conventional method, the macroeconomic impact of the technical improvement simply reflects the switching of demand between different commodities within the household budget. Commodities, which have, directly or indirectly, more domestic content will have a larger impact on GDP. In the present case, this switching depends on the degree of substitution between private transport and the composite commodity 'all other goods', and between fuel and vehicles in the production of private transport. GDP falls when, following the efficiency change, the consumer reduces expenditure on the consumption of all other goods competing with private transport, and increases the consumption of fuel. However, I recognise that the structure of consumption adopted here is extremely rudimentary. In practice the demand impact will depend heavily on changes in demand for other commodities that are close substitutes and complements to private transport. For example, I would expect consumers to substitute between public and private transport.

When the adjusted *cpi* is used, the price of private transport, which is normally unobserved, is incorporated into the calculation of the real wage. With a fixed real wage, I then report an increase in competitiveness and a productivity-led economic stimulus. This is because the nominal wage falls. This reduces domestic prices, stimulating the demand for exports, and reducing the demand for imports. It also leads to some substitution of labour for capital. When workers are able to bargain, the real wage will rise as the unemployment rate falls, limiting the reduction in the *cpi*, the nominal wage and the subsequent increase in economic activity.

5.8 Conclusions

In this paper I have four main aims. First, I attempt to model the use of energy-intensive consumer services in a more appropriate manner than the conventional approach in the literature. In particular, I operationalise the approach suggested by Gillingham et al. (2016) by explicitly incorporate both energy and non-energy inputs to the supply of the energy-intensive service and the determination of its price. I adopt, as an example, the household production of private transport services using inputs of refined fuels and motor vehicles and I incorporate this approach into a Computable General Equilibrium model for the UK.

Second, I analyse the impact of an efficiency improvement in the provision of this energy-intensive service. I distinguish between energy- and vehicle-improving technical changes and discuss this in a partial and general equilibrium context.

Third, I investigate, through simulation, the conditions under which an increase in the efficiency of vehicles in the production of private transport reduces the fuel use in the economy as a whole. The empirical results from the CGE modelling show that when the elasticity of substitution between motor vehicles and refined fuels is greater than the elasticity of substitution between private transport and all other goods, as long as any positive aggregate output effects are not too large, the consumption of refined fuels falls.

Fourth, I consider the impact of technical change in the household consumption sector on the aggregate level of economic activity. Where the consumer price index is calculated in the standard way, the aggregate effect on economic activity is very small and can be positive or negative. This impact is driven solely by the changes in the composition of household demand and the direct, indirect and induced domestic content of the affected sectors. However, when the price of private transport, which is normally not observed, is included in the calculation of *cpi*, the fall in the price index reduces the nominal wage and improves competitiveness in the economy as a whole. This produces a positive economic stimulus.

This work provides a more sophisticated treatment of private transport demand, as a household self-produced energy-intensive service. While in this paper I investigate the consequences a technical improvement in motor vehicles, the modelling framework is clearly suited for the analysis of technical progress in refined fuels or both vehicle and fuels at the same time. In fact, I plan in future research, to extend this work to derive a set of conditions that specify under which circumstances technical progress in motor vehicles use delivers a better outcome than a refined fuel efficiency improvement (and vice versa), in terms of reduced fuels use and economic stimulus.

Another natural extension would be to model other energy intensive services, such as home heating, in a similar way. Here it is crucial to obtain accurate estimates of the relevant elasticities of substitution because the results are sensitive to their values. Furthermore, the adoption of new technological vintages, such as in motor vehicles, require investment. The accumulation of the new stock of vehicles should be modelled as a formal investment process similar to the way I model capital stock accumulation in the production side of the economy. However, whilst this will affect the time path of the introduction of the more efficient technology, it does not affect the long-run analysis applied here. Finally, in the specific case of motor vehicles, fuels savings from an efficiency improvement have often been offset by the increase in size and weight of vehicles. A more sophisticated way of modelling private transport services should therefore identify a framework where variations in these characteristics are linked to fuel efficiency.

Chapter 6

Conclusions, extensions and plans for future research

6.1 Contributions to, and general lessons for, the analysis of household energy efficiency improvements

In this thesis I have analysed the system-wide implications of households' energy efficiency improvements in Scotland and the UK. The analysis is conducted by focussing on three main aspects of energy efficiency and its impacts, reflected in three main self-contained, but interconnected, papers in Chapters 3, 4 and 5.

In Chapter 3 I investigate the implications of moving from the national case of the UK to the regional case of Scotland in the analysis of an across the board 5% increase in households' energy efficiency. I find that energy efficiency improvements deliver an overall stimulus to the regional economy through boosted real income combined with an increase in the demand for non-energy goods. That is, increased household energy efficiency manifests as a straightforward net demand boost to the wider economy. This has a positive impact on employment, investment and overall GDP. When I assume no interregional migration of workers, I find that some of the exports are crowded out by rising domestic prices, a similar finding to that reported for the national UK case in Lecca et al. (2014a). On the other hand, when interregional migration is introduced, this acts to drive domestic prices back to their baseline in the long-run as labour supply is augmented, so that exports fully recover, and there is a greater GDP expansion. Nevertheless, there is a net decrease in household energy consumption, accompanied by a net decrease in industrial energy use. However, there are positive rebound effects at household and economy-wide levels, indicating that actual energy savings are proportionately smaller than may be expected in pure engineering terms as a result of an increase in energy efficiency. Furthermore, I conclude that there is a trade-off between the achieved energy savings and the scale of the GDP stimulus; that is the bigger the economic stimulus from improved household energy efficiency the higher the rebound is likely to be (though the exact magnitude of both will depend on the composition of economic activity).

In this first paper I also explore the implications of allowing for the greater fiscal autonomy that the Scottish Government is in the process of acquiring. I find that, since the household energy efficiency improvement delivers a small economic expansion, the government enjoys higher revenue from taxes. When the Government uses the extra revenue to increase its current expenditure we have an additional positive demand shock. On the other hand, when revenues are recycled to reduce income tax rates, this has also positive supply side effects that add to the demand stimulus through increased consumption. This is because the real after tax consumption wage increases, and there is downward pressure on nominal wage demands.

Overall, the first paper adds to the still thin literature of system wide impacts of household energy efficiency improvements. Apart from being the first study that examines the case of Scotland, it proposes for the first time energy efficiency improvements as an instrument of regional development policy. This is relevant in a current policy debate where the Scottish Government have identified energy efficiency as a national infrastructure priority (The Scottish Government, 2017b) and, in September 2016, the

First Minister announced public spending on energy efficiency as part of a post-Brexit stimulus package. Moreover, it provides a first attempt to analyse the implications of such development policy in the context of a fiscally devolved Scotland. Results from the study can directly input into the Scottish energy policy debate, given that the recently released Scottish Energy Strategy (The Scottish Government, 2017b) highlights the key role of energy efficiency in pursuing its energy and climate objectives.

In the second paper, (Chapter 4), I analyse the distributional impact of improving household residential energy use in the UK. That is, the use of gas and electricity in delivering household heating and lighting. Here I focus also on potential options for government to fund the efficiency improvement programmes via either a temporary increase in income tax rates or a temporary reallocation of government spending as compared to a costless energy efficiency improvement. I argue that the economic expansion from the increased household energy efficiency could provide a justification for public support of energy efficiency programmes, linking with the IEA (2014) multiple benefits argument (as with the findings in the first paper).

Specifically, I question whether only those households that are more likely to be in fuel poverty should receive help to increase their residential energy efficiency, or whether there is sufficient economic expansion to justify wider support. This is explored by contrasting the results of simulations in which a 10% residential energy efficiency improvement occurs in all households with one where only the poorest household income group (which corresponds to the lowest income quintile) experiences the improvement.

I find that an improvement in residential energy efficiency across all households delivers a bigger stimulus to the economy than improving only some household's energy efficiency. This is because both a larger base of households receives the efficiency improvement, and because, in contrast to lower income groups, inclusion of higher income households reduces reliance on transfers from the Government, with these households benefiting more from endogenous changes in labour and capital incomes. In fact, improving only the lowest household income group efficiency still delivers a small net stimulus to the economy, which is one tenth of the stimulus delivered by improving all household's energy efficiency in terms of GDP. However, the income increase for lower income households is 80% of what it would be when all household benefit from higher efficiency.

When the Government provides support for energy efficiency, I find that a temporary reallocation in government spending creates less distortion in the economy than a rise in income tax rates. This is because income tax rate influences the real take home wage and this adversely impacts the supply side of the economy, as workers seek to restore their net-of-tax real wage. Particularly when efficiency improves only in the poorest household group, a 10% increase in energy efficiency is not sufficient to generate a net long-run GDP expansion; rather it actually delivers a small net contraction, because all households pay higher income taxes but only one group (the lowest income group with the least spending power) enjoys the higher efficiency. On the other hand, a temporary government spending reallocation delivers a small medium term and long-run GDP expansion. However again, when lower income households are targeted, the income gains are very close in all cases.

On the basis of these findings, my recommendation would be that governments should carefully consider supporting energy efficiency improving programmes in order to realise a wider set of sustained economic benefits, but also evaluate which policy instrument delivers the best overall economic impact, depending on its priority. While improving all households' efficiency in energy use delivers a higher stimulus, it also raises the overall energy use in the economy (across industry as well as in household personal transportation). On the other hand, when only poorer households become more energy efficient, there is a smaller stimulus, but the targeted group retains most of the income gains that allow it to consume more energy and benefit from better heating and lighting.

This second paper contributes to the literature in at least three respects. Firstly, while the previous literature has focussed predominantly on rebound effects from improved households' energy efficiency. Here I propose and implement a system wide approach and analyse the impact of energy efficiency on the economy as a whole. By taking this perspective, the presence of rebound effects is only one of the impacts of the increased efficiency that has to be balanced against a set of macroeconomic impacts.

Secondly, while past studies have typically explored the impact of household energy efficiency on the aggregate household sector, here I study the distribution of such impact on five different household income groups. This allows me to assess the extent to which energy efficiency policy actions are able to deliver in terms of inclusive growth and accessibility of energy.

Finally, past CGE studies in the same field have assumed that improving energy efficiency is costless. Although this assumption can be useful to isolate the pure impact of efficiency, costs involved in the implementation of efficiency measures can impact both the actual energy savings and the wider economy. For this reason I explore the case where the Government pays for efficiency via different mechanisms. Ideally, the simulation scenarios could be repeated in consultation with the Government using real estimates of energy efficiency improving investments, to assess their impact on energy use and on the economy. This is a focus of current research building on my thesis work.

In the third paper, (Chapter 5), I consider the impact of technical progress that is not directly energy saving on households fuels consumption, and on the wider economy. To this end, I develop a partial equilibrium model in which households do not consume energy directly, but they use energy together with energy powered appliances to produce energy services that are energy intensive. I use the example of private transport as being composed of refined fuels and motor vehicles, by imagining that households self-produce private transport and consume it directly. Using diagrams, I illustrate the case where technical improvement in motor-vehicles deliver reduced refined fuels use and impacts the demand for private transport. I find that this depends on the substitutability between the inputs of motor vehicles and fuels, and on the substitutability between private transport and other goods and services.

I incorporate the partial equilibrium model illustrated in the first part of the paper into a CGE model for the UK. By simulating a 10% improvement in vehicles efficiency I find that the CGE model delivers results that are largely consistent with the partial equilibrium framework. I use the

CGE model to assess the system wide impact of technical progress in households' use of motor vehicles. Here I find that a small economic stimulus is delivered for elasticity values for which the technical progress triggers a net increase in demand. However, when I calculate the *cpi* to include the price of the composite good private transport, which is normally non observable, the adjusted *cpi* decreases, and this stimulates the economy through competitiveness.

The contribution of the work to the literature in this case is both theoretical and empirical. The previous literature has often modelled energy as if it is consumed directly, or considered energy services composed of technology and physical energy where technology only in terms of transforming physical energy in energy services. This implies that that the price of the service is a function of the price of physical energy and efficiency of energy use. Here, I show how energy services can be modelled as composite goods of physical energy and technology and that technical improvements in both inputs can potentially reduce (or increase) physical energy use and influence the price of the service. While, for simplicity, I use the example of private transport, the modelling framework can be easily extended (where appropriate data are available) to consider other services such has home heating. Using this framework it is possible to identify the implicit price of private transport (or any other energy intensive service). This price can then be used to adjust the calculation of the *cpi* and this has significant implications for the economy-wide impact of technical improvements in the production of motoring services.

From a policy perspective, this paper shows how a reduction in physical energy can be achieved through technical progress that is not directly fuel' saving depending on the substitutability between fuels and vehicles, and on the price elasticity of private transport service.[1] Furthermore, the macroeconomic impact of such efficiency improvements can deliver a positive stimulus to the economy, especially if the *cpi* is adjusted to account for the increased efficiency in consumer goods, such as motor vehicles, as Gordon (2016) suggests. Based on this findings my recommendation would be that governments should not only focus on energy efficiency improvements but look more in generally at technical progress in designing policy initiatives that simultaneously reduce energy use and carbon emissions and maintain or stimulate economic development.

6.2 Contributions to CGE modelling of household energy efficiency changes

Throughout the thesis, the impact of efficiency improvements in household's energy use are analysed using CGE modelling techniques. The choice of this modelling approach reflects my concern with the several system-wide ramifications of household energy efficiency changes. Providing this analysis has involved the development of parts of existing Scottish and UK CGE models, named AMOS-ENVI and UK-ENVI respectively, to consider the specific research issues that are the focus of each chapter. Specifically, I focus on the household consumption side and develop alternative consumption models that can be adopted for the

[1] Clearly, the same modelling set-up can be used to analyse the impact of fuel saving technical improvements, and again it is possible to identify a range of elasticity values that will always deliver a reduction in fuel use.

analysis of potential energy policies. This includes also the development of my own computer codes of the model in GAMS.

In Chapter 3 I take the most recent version of the AMOS-ENVI model used in (Lecca et al., 2013) and extend it to include a consumption function that reflects the decision of a representative household consuming energy and non-energy goods as imperfect substitutes.

In Chapter 4, I extend the UK-ENVI model in Lecca et al. (2014a) by modifying the consumption function so that residential energy use, the consumption of energy for transport, and the consumption of non-energy use, are considered alternative choices for the consumer. In this work, I also try to improve the assumption of a single forward looking household utility maximiser, by separately modelling the preferences of five different household groups corresponding to five different agents. Moreover, I introduce mixed expectations in the model for the first time, by assuming that while households are myopic, investors are forward looking profit maximisers. Potentially, the model can also accommodate mixed expectations formation processes between the different household groups, so that some groups can be myopic and others forward looking. This constitutes a step towards the development of a behavioural CGE model of household consumption.

Finally, in Chapter 5, I further extend the UK-ENVI model and consider household energy-intensive commodities by using the example of private transport. Specifically, I assume that household self-produce private transport, for which there is no corresponding supply sector, by combining motor vehicles and refined fuels purchased from the corresponding supply sectors, and then consume it directly without selling it into a market. This implies that this framework can capture the implicit price of private transport and it depends on both the price of vehicles and the price of fuels. In this setting it is possible to analyse how even technical progress that is not fuel saving can have an impact on fuel use. Moreover, it allows me to adjust the calculation of the *cpi* by using the price of private transport.

6.3 Extensions and plans for the future

With this work I show that energy efficiency proves to be much more than simply an instrument for the reduction of final energy use. In fact, I show that, with energy efficiency improvements it is possible to simultaneously deliver a reduction in energy use, reduce inequality and energy inequality, and stimulate the wider economy. I also show that other types of technical progress can deliver both in terms of physical energy use reduction and stimulus to the economy, when these occur in the technology input of energy intensive services. For this reason, I believe that future research should focus more on double or even multiple dividends and multiple benefits of energy efficiency policies, and not be limited solely to the assessment of the rebound effect, as this may discourage policy makers from properly evaluating the effectiveness of energy efficiency improvement as an energy policy instrument of wider economic policy, as well as energy policy, conventionally defined.

The analysis in this thesis focusses on the cases of the UK and Scotland, and tackles only some of the complex issues that are linked to energy efficiency and energy programmes in general. Moreover, the economic modelling frameworks used in this work could be improved potentially to increase the depth and the accuracy of the analysis. Here, I outline some potential extensions of this work, which also form plans for future research.

First, because my focus is on both Scotland and the UK, one natural extension is to look at the impacts of energy efficiency in an explicitly interregional setting, by developing and applying a two region model of Scotland and the Rest of UK (RUK). This enables consideration of interregional feedback and spillover effects. In fact, Scotland and the rest of UK are two highly integrated regions of the same country, with strong links in trade, labour market, regulations and other policies. Any impact from energy efficiency changes (and any other policy) in one region would necessarily impact the other, and this would ultimately influence the overall impact of such policies, in Scotland, the RUK and the UK as a whole.

The interregional setting is also particularly important for the evaluation and implementation of new energy policies in the light of the new devolved fiscal powers that Scotland is in the process of acquiring, and of the decision of the UK to leave the European Union. Any analysis involving asymmetric policies between the two regions should not neglect the connections between the central and the devolved governments, and their links through the goods and job market. For example, the 'no detriment' principle whereby fiscal decisions in Scotland should not adversely impact the rest of UK and vice versa, can be hugely important in the assessment of the implications of energy policies in a fiscally devolved Scotland, or in a (at least temporarily) less internationally integrated UK. To this end, I have recently been working with an interregional model of Scotland and RUK to look at impacts of future potential trade agreements in light of new international scenarios including the possibility of leaving the European single market area.[2] My plan is to develop the CGE model used in this analysis in order to have a multiregional energy model of Scotland and RUK, which in principle is able to deal with energy-economic-environment issues in a wider and more complex (and complete) spatial framework.

Second, both the Scottish and the UK Governments have now adopted an energy systems model called TIMES.[3] This is a modelling tool that generates energy systems for a given geographic area, by minimising the cost of delivering energy given a set of constraints. Although TIMES is a useful tool to inform decisions on energy systems implementation, it is not capable of analysing the economic impact of these systems. Given the extent of the interrelation of the energy economy and environmental sub-systems, TIMES use should be supported by other modelling approaches such as CGE models. For this reason there is wide interest in understanding how TIMES and an energy CGE model may be linked and how policy makers should use these two modelling frameworks to inform their decisions. For instance, TIMES takes some economic parameters exogenously, such as GDP trends and prices, which could be taken from a CGE model. On the other hand, CGE models could use bottom-up information on energy supply curves from TIMES (see for example Bye et al., 2015; Fortes et al., 2014). Currently, I am involved in a research

[2]The output of this research is summarised in Roy et al. (2016)

[3]TIMES is the acronym of The Integrated MARKAL-EFOM System. In turn MARKAL is the acronym of Market Allocation and EFOM is Energy Flow Optimisation Model.

project that is starting to explore possible links between the Scottish CGE model developed in this thesis and the Scottish TIMES model.[4] However the work is still in its initial stages.

Third, CGE models' micro foundations rely on assumptions that may not entirely reflect the structure of real economic systems. A growing literature in behavioural economics is constantly challenging some of the neo-classical impositions in economic theory, and this stimulates a debate on the micro foundations of CGE models. For this reason, I believe that it is important to test the implication of incorporating elements of behavioural economics into the CGE framework, and to move, when appropriate, towards a behavioural CGE model.

In this thesis I have already taken some steps in this direction, by introducing different expectations formation processes between consumption (myopic) and investment (forward-looking) behaviour (see Chapter 4) to reflect the fact that households have less foresight than firms. However, here there are a number of models that we can borrow from behavioural economics that would represent intermediate steps between full myopic and completely forward-looking consumers. For instance, the forward looking consumption behaviour assumes that consumers discount future utility, at a constant rate over time. However, empirical and experimental research find (Laibson, 1997) that individuals may have declining rates of time preference, which means that they discount more over a longer period of time. This behaviour has been described as *hyperbolic discounting*, to reflect the fact that consumers are impatient and

[4] The project started in September 2016. Details can be found here https://pure.strath.ac.uk/portal/en/projects/climatexchange-201617(dbdda63d-51da-48da-a64c-cdaf0076798a).html

draw more utility from consumption over a shorter period of time, and therefore their discounted function takes the form of a hyperbola.

Another interesting intermediate case is the idea that consumers exhibit some *habit formation* behaviour (Boldrin et al., 2001; Sundaresan, 1989). In the myopic consumption model, consumers base their consumption on current disposable income, while in the forward looking model they base consumption decisions on future discounted wealth. In habit formation models, consumer's preferences can be affected by past levels of consumption. This habit can also be linked to external aggregate consumption rather than only to the consumer's past consumption, to reflect the fact that consumption decisions are influenced by the current state of the economy.

From the production side of the model, the assumption of perfectly competitive firms may be challenging to support in the market for energy where most firms operate in an oligopolistic or monopolistic competition setting (see for example Balistreri and Rutherford, 2013). Here, together with the research group of the Centre for Energy Policy and the Fraser of Allander Institute of the University of Strathclyde, I am already looking at improving the representation of the electricity sector. Specifically we are looking at the impact of modelling this industry as a monopoly, oligopoly and monopolistic competitive sector, starting from the limiting case, where the price of electricity is exogenous and not determined in the market.

Fourth, energy efficiency is only one of the instruments used by policy makers in trying to meet ambitious energy and environmental targets. As we have seen this instrument is relevant not only for the impact on final energy use but also for the wider economic implications. However, there are other policies that can be used together with energy efficiency to deliver on these objectives, and to which the modelling framework developed in this thesis would be immediately applicable. For example, interest is growing in carbon capture and storage (CCS) technologies are becoming more popular in Scotland and the UK, for the potential impact of investment in the sector and on the possibility of retaining more carbon intensive activities, by 'cleaning' their emissions. Analysis of the energy-environment-economic implications of the introduction of such technology can in principle be analysed using the modelling framework developed in this thesis, provided that adequate data are available, even though in this case there are issues related with the introduction of a new technology.

Alternative energy sources such as renewables are also very popular especially in Scotland. Here price mechanisms such as induced substitution via improved efficiency, or other instruments, can be analysed in a CGE framework in order to assess the impact of increasing the share of energy produced by renewables consumed by households, and the wider implications for the economy. For example, should an energy efficiency improvement in household consumption result in a higher consumption of energy produced by renewables this could where there is less concern about the rebound effect given the negligible impact on carbon emissions.

Finally, another interesting focus would be carbon taxes and other energy or environmental taxes. Although these are a controversial instrument, because they may induce distortionary effects in the economy, and cause pollution spillover, the carbon tax is regarded by some economists as an effective instrument to reduce carbon emissions and preserve natural resources. Moreover, in the case where carbon taxes are compensated by a reduction in other type of taxes, such as income tax, the distortionary effects can be minimised, as has been shown in a past Scottish focussed study (Allan et al., 2014). Again, given the increasing devolved fiscal powers that Scotland is set to enjoy in the near future, carbon taxes should be regarded as an interesting subject in the context of UK regions interactions under different fiscal regimes.

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Appendices

A The mathematical presentation of the AMOS and UK-ENVI models

A.1 The default model

Prices

$$PM_{i,t} = \overline{PM_i} \tag{A.1}$$

$$PE_{i,t} = \overline{PE_i} \tag{A.2}$$

$$PQ_{I,T} = \frac{PR_{i,t} \cdot Ri,t + PM_{i,t} \cdot Mi,t}{Ri,t + Mi,t} \tag{A.3}$$

$$PIR_{I,T} = \frac{\sum_i VR_{i,j,t} \cdot PRj,t + \sum_i VI_{i,j,t} \cdot \overline{PI}_{j,t}}{\sum_i VIRi,j,t} \tag{A.4}$$

$$PY_{j,t} \cdot a_j^Y = \left(PR_{j,t} \cdot (1 - btax_j, sub_j, dep_j) - \sum_i a_{i,j}^y PQj,t \right) \tag{A.5}$$

$$UCK_t = PK_t \cdot (r + \delta) \tag{A.6}$$

$$PC_t^{1-\sigma^C} = \sum_j \delta_j^f \cdot PQ_t^{1-\sigma^C} \tag{A.7}$$

$$PG_t^{1-\sigma^G} = \sum_j \delta_j^g \cdot PQ_t^{1-\sigma^G} \tag{A.8}$$

$$w_t^b = \frac{w_t}{1 + \tau_t} \tag{A.9}$$

$$ln\left[\frac{w_t}{cpi_t}\right] = \varphi - \epsilon ln(u_t) \tag{A.10}$$

$$rk_{j,t} = PY_{j,t} \cdot \delta_j^k \cdot A^{Y\varrho_j} \cdot \left(\frac{Y_{j,t}}{Kj,t}\right)^{1-\varrho_j} \tag{A.11}$$

$$Pk_t = \frac{\sum_j PY_{j,t} \cdot \sum_i KM_{i,j}}{\sum_{i,j} KM_{i,j}} \tag{A.12}$$

Production technology

$$X_{i,t} = A_i^X \cdot \left[\delta_i^y \cdot Y_{i,t}^{\rho_i^X} + (1-\delta_i^V) \cdot V^{\rho_i^X} i,t\right]^{\frac{1}{\rho_i^X}} \tag{A.13}$$

$$Y_{j,t} = \left(A^{x\rho_j^X}\delta_i^y \cdot \frac{PQ_{j,t}}{PY_{j,t}}\right)^{\frac{1}{1-\rho_j^x}} \cdot X_{i,t} \tag{A.14}$$

$$V_{j,t} = \left(A^{x\rho_j^X}(1-\delta_i^y) \cdot \frac{PQ_{j,t}}{PV_{j,t}}\right)^{\frac{1}{1-\rho_j^x}} \cdot X_{i,t} \tag{A.15}$$

$$v_{i,t} = A_i^v \cdot \left[\delta_i^v \cdot E_{i,t}^{\rho_i^V} + (1-\delta_i^V) \cdot NE^{\rho_i^V} i,t\right]^{\frac{1}{\rho_i^V}} \tag{A.16}$$

$$\frac{E_{j,t}}{E_{j,t}} = \left[\left(\frac{\delta_j^v}{1-\delta_j^v}\right) \cdot \left(\frac{PNE_{j,t}}{PE_{j,t}}\right)\right]^{\frac{1}{1-\rho_j^v}} \tag{A.17}$$

$$VV_{ze,j,t} = \left(A^{z\rho_j^z}(1-\delta^E N_i) \cdot \frac{PNE_t}{PQ_{E,t}}\right)^{\frac{1}{1-\rho_j^E}} \cdot E_{i,t} \tag{A.18}$$

$$Y_{i,t} = A_i^Y \cdot \left[\delta_i^k \cdot K_{i,t}^{\rho_i^Y} + \delta_i^l \cdot L^{\rho_i^Y} i,t\right]^{\frac{1}{\rho_i^Y}} \tag{A.19}$$

$$L_{j,t} = \left(A^{x\rho_j^Y} \delta_i^l \cdot \frac{PY_{j,t}}{w_t} \right)^{\frac{1}{1-\rho_j^Y}} \cdot Y_{j,t} \tag{A.20}$$

Trade

$$VV_{i,j,t} = Y_i^{vv} \cdot \left[\delta_i^{vm} \cdot VM_{i,t}^{\rho_i^A} + (1 - \delta_i^{vir}) \cdot VIR^{\rho_i^A} i, t \right]^{\frac{1}{\rho_i^A}} \tag{A.21}$$

$$\frac{VM_{i,j,t}}{VIR_{i,j,t}} = \left[\left(\frac{\delta_j^{vm}}{1 - \delta_j^{vir}} \right) \cdot \left(\frac{PIR_{i,t}}{PM_{i,t}} \right) \right]^{\frac{1}{1-\rho_j^A}} \tag{A.22}$$

$$VIR_{i,j,t} = Y_i^{vir} \cdot \left[\delta_i^{vi} \cdot VI_{i,t}^{\rho_i^A} + (1 - \delta_i^{vr}) \cdot VM^{\rho_i^A} i, t \right]^{\frac{1}{\rho_i^A}} \tag{A.23}$$

$$\frac{VR_{i,j,t}}{VI_{i,j,t}} = \left[\left(\frac{\delta_j^{vr}}{1 - \delta_j^{vi}} \right) \cdot \left(\frac{PI_{i,t}}{PR_{i,t}} \right) \right]^{\frac{1}{1-\rho_j^A}} \tag{A.24}$$

$$E_{i,t} = \bar{E}_t \cdot \left(\frac{PE_{i,t}}{PQ_{i,t}} \right)^{\rho_i^x} \tag{A.25}$$

Regional (or national in UK ENVI) demand

$$R_{i,t} = \sum_i VR_{i,j,t} + \sum_i QHR_{i,h,t} + QVR_{i,t} + QGR_{i,t} \tag{A.26}$$

Total absorption equation

$$X_{i,t} + M_{i,t} = \sum_i VV_{i,j,t} + \sum_i QH_{i,h,t} + QV_{i,t} + QG_{i,t} + E_{i,t} \tag{A.27}$$

Households and other domestic institutions

$$U^t(c_t) = \sum_{i=1}^{T-t}(1+\rho)^{-t}\frac{C_t^{1-\sigma}-1}{1-\sigma} \tag{A.28}$$

$$\frac{C_t}{C_{t+1}} = \left[\frac{PC_t \cdot (1+\rho)}{PC_{t+1} \cdot (1+r)}\right]^{-\frac{1}{\sigma}} \tag{A.29}$$

$$W_t = NFW_t + FW_t \tag{A.30}$$

$$NFW_t(1+r) = NFW_{t+1} + (1-\tau_t)L_t^s(1-u_t)w_t + Trf_t \tag{A.31}$$

$$FW_t(1+r) = FW_{t+1} + \Pi_t + S_t \tag{A.32}$$

$$Trf_t = Pc_t \cdot \overline{Trf} \tag{A.33}$$

$$S_t = mps \cdot [(1-\tau_t)\, L_t^s(1-u_t)w_t + Trf_t] \tag{A.34}$$

$$QH_{z,t} = \left(\delta^{f\rho_i^c} \cdot \frac{Pc_t}{PQ_{z,t}}\right)^{rho_i^c} \cdot NEc_t \tag{A.35}$$

$$QH_{I,t} = \gamma_i^f \left[\delta^{hir} QHIR_t^{\rho_i^A} + (1-\delta^{hm})QHM_t^{\rho_i^A}\right]^{\frac{1}{\rho_i^A}} \tag{A.36}$$

$$\frac{QHIR_{i,t}}{QHM_{i,t}} = \left[\left(\frac{\delta_i^{hir}}{1-\delta_i^{hm}}\right) \cdot \left(\frac{PM_{i,t}}{PR_{i,t}}\right)\right]^{\frac{1}{1-\rho^A}} \tag{A.37}$$

$$QHIR_{I,t} = \gamma_i^{fir} \left[\delta^{hr} QHR_t^{\rho_i^{hr}} + \delta^{hi} QHI_t^{\rho_i^A} \right]^{\frac{1}{\rho_i^A}} \quad (A.38)$$

$$\frac{QHR_{i,t}}{QHI_{i,t}} = \left[\left(\frac{\delta_i^{hr}}{1 - \delta_i^{hi}} \right) \cdot \left(\frac{PI_{i,t}}{PR_{i,t}} \right) \right]^{\frac{1}{1-\rho^A}} \quad (A.39)$$

Government

$$\begin{gathered} FD_t = \overline{G_t} \cdot PG_t + \sum_{dgins} TRG_{dngins,t} \cdot PC_t - \\ \left(d^g \cdot \sum_i rki,t \cdot K_{i,t} + \sum_i IBTi,t + \sum_i Lj,t \cdot w_t + \overline{FE}\epsilon_t \right) \end{gathered} \quad (A.40)$$

In the national model a balanced budged constraint is assumed and Government consumption becomes endogenous.

$$QG_{i,t} = \delta_i^g \cdot G_t \quad (A.41)$$

$$QGR_i, t = QG_i, t; QGM_i, t = 0; \quad (A.42)$$

Investment demand

$$QV_{i,t} = \sum_j KM_{i,j} \cdot J_{j,t} \quad (A.43)$$

$$QV_{I,t} = \gamma_i^v \left[\delta^{qvm} QVM_t^{\rho_i^A} + (1 - \delta^{qvir}) QVIR_t^{\rho_i^A} \right]^{\frac{1}{\rho_i^A}} \quad (A.44)$$

$$\frac{QVM_{i,t}}{QVIR_{i,t}} = \left[\left(\frac{\delta_i^{qvm}}{\delta_i^{qvir}} \right) \cdot \left(\frac{PIR_{i,t}}{PM_{i,t}} \right) \right]^{\frac{1}{1-\rho^A}} \quad (A.45)$$

$$QVIR_{I,t} = \gamma_i^{vir}\left[\delta^{qvi} QVI_t^{\rho_i^A} + (1-\delta^{qvr}) QVR_t^{\rho_i^A}\right]^{\frac{1}{\rho_i^A}} \tag{A.46}$$

$$\frac{QVR_{i,t}}{QVI_{i,t}} = \left[\left(\frac{\delta_i^{qvr}}{\delta_i^{qvi}}\right) \cdot \left(\frac{PI_{i,t}}{PR_{i,t}}\right)\right]^{\frac{1}{1-\rho^A}} \tag{A.47}$$

Time path of investment

$$J_{i,t} = I_{i,t}\left(1 - bb - tk + \frac{\beta}{2}\frac{\left(\frac{I_{i,t}}{K_{i,t}} - \alpha\right)^2}{\frac{I_{i,t}}{K_{i,t}}}\right) \tag{A.48}$$

$$\frac{I_t}{K_t} = \alpha + \frac{1}{\beta}\cdot\left[\frac{\lambda_{i,t}}{Pk_t} - (1 - bb - tk)\right] \tag{A.49}$$

$$\dot{\lambda}_{i,t} = \lambda_{i,t}(r_t + \delta) - R_{i,t}^k \tag{A.50}$$

$$\theta(x_t) = \frac{\beta}{2}\frac{(x_t - \alpha)^2}{x_t}; \text{and } x_t = \frac{x_t}{k_t} \tag{A.51}$$

$$R_{i,t}^k = rk_t - Pk + t\left[\frac{I_{i,t}}{K_{i,t}}\right]^2 \theta_t'(I/K) \tag{A.52}$$

Factors accumulation

$$KS_{i,t+1} = (1-\delta)KS_{i,t} + I_{i,t} \tag{A.53}$$

$$K_{i,t} = KS_{i,t} \tag{A.54}$$

$$LS_{t+1} = (1+\zeta-v^u \left[ln(u_t) - ln(\bar{u}^N)\right]+v^w \left[ln(w_t/cpi_t) - ln(\bar{w}^N/\overline{cpi}^N)\right])\cdot LS_t \tag{A.55}$$

Equation (A.55) *is only appears in AMOS-ENVI*

$$LS_t \cdot (1 - u_t) = \sum_j L_{j,t} \tag{A.56}$$

Indirect taxes and subsidies

$$IBT_{i,t} = btax_i \cdot X_{i,t} \cdot PQ_{i,t} \tag{A.57}$$

Total demand for import and current account

$$M_{i,t} = \sum_i VI_{i,j,t}+\sum_i VM_{i,j,t}+\sum_i QHM_{i,h,t}+QGM_{i,t}+QVI_{i,t}+QVM_{i,t} \tag{A.58}$$

$$TB_t = \sum_i M_{i,t} \cdot PM_{i,t} - \sum_i E_{i,t} \cdot PE_{i,t} + \epsilon \cdot \left(\sum_{dngins} \overline{REM}_{dngind} + \overline{FE}\right) \tag{A.59}$$

Assets

$$VF_{i,t} = \lambda_{i,t} \cdot K_{i,t} \tag{A.60}$$

$$D_{t+1} = (1 + r) \cdot D_t + TB + t \tag{A.61}$$

$$Pg_{t+1} \cdot GD_{t+1} = \left[1 + r + \left(\frac{Pc_{t+1}}{Pc_t} - 1\right)\right] \cdot PG_t \cdot Gd_t + FD_t \quad (A.62)$$

Steady state conditions

$$\delta \cdot KS_{i,T} = I_{i,t} \quad (A.63)$$

$$R^k_{i,T} = \lambda_{i,T}(r + \delta) \quad (A.64)$$

$$FD_t = \left[1 + r + \left(\frac{Pc_{t+1}}{Pc_t} - 1\right)\right] \cdot PG_t \cdot Gd_t \quad (A.65)$$

$$TB_T = r \cdot D_t \quad (A.66)$$

$$NFW_t \cdot r = (1 - \tau_t)L^s_t(1 - u_t)w_t + Trf_t \quad (A.67)$$

$$FW_t \cdot r = \Pi - S_t + Trf_t \quad (A.68)$$

To produce short-run and long-run results

$$KS_{i,t=1} = KS_{i,t=0} \quad (A.69)$$

$$LS_{i,t=1} = LS_{i,t=0} \quad (A.70)$$

$$GD_{i,t=1} = GD_{i,t=0} \tag{A.71}$$

$$D_{i,t=1} = D_{i,t=0} \tag{A.72}$$

A.2 Extensions to AMOS-ENVI for Chapter 3

Prices

$$PNE_t = \frac{\sum_z PQ_{z,t} \cdot \bar{V}_z}{\sum_z PQ_z \cdot \bar{V}_z} \tag{A.73}$$

$$PEN_t = \frac{\sum_E PQ_{E,t} \cdot \bar{V}_E}{\sum_E PQ_E \cdot \bar{V}_E} \tag{A.74}$$

Consumption

$$C_t = \left[\delta^E (\gamma EC_t)^{\rho_e} + (1-\delta^E) NEC_t^{\rho_e}\right]^{-\frac{1}{\rho_e}} \tag{A.75}$$

$$Ec_t = \left(\gamma^{\varepsilon} \delta^E \cdot \frac{Pc_t}{PEN_t}\right)^{\frac{1}{1-\rho_e}} \cdot C_t \tag{A.76}$$

$$Ec_t = \left[\delta^{co} CO_t^{\rho_g} + (1-\delta^{co}) EG_t^{\rho_g}\right]^{\frac{1}{\rho_g}} \tag{A.77}$$

$$\frac{CO_t}{EGc_t} = \left[\left(\frac{\delta^{co}}{1-\delta^{co}}\right) \cdot \left(\frac{PEG_t}{PCO_t}\right)\right]^{\frac{1}{1-\rho^g}} \tag{A.78}$$

$$CO_t = \left[\delta^{cl} CL_t^{\rho_o} + (1-\delta^{co}) OIL_t^{\rho_o}\right]^{\frac{1}{\rho_o}} \tag{A.79}$$

$$\frac{CL_t}{OIL_t} = \left[\left(\frac{\delta^{cl}}{1-\delta^{cl}}\right)\cdot\left(\frac{PQ_{oil,t}}{PQ_{coal,t}}\right)\right]^{\frac{1}{1-\rho^0}} \tag{A.80}$$

$$QH_{z,t} = \left(\delta^{f\rho_i^c}\cdot\frac{Pc_t}{PQ_{z,t}}\right)^{rho_i^c}\cdot NEc_t \tag{A.81}$$

$$EG_t = \left[\delta^{Ele}Ele_t^{\rho_{el}} + (1-\delta^{el})GAS_t^{\rho_{el}}\right]^{\frac{1}{\rho_{el}}} \tag{A.82}$$

$$\frac{Ele_t}{GAS_t} = \left[\left(\frac{\delta^{GAS}}{1-\delta^{GAS}}\right)\cdot\left(\frac{PQ_{GAS,t}}{PQ_{Ele,t}}\right)\right]^{\frac{1}{1-\rho^{el}}} \tag{A.83}$$

$$QH_{ele,t} = Ec_t \tag{A.84}$$

$$QH_{GAS,t} = GAS_t \tag{A.85}$$

$$QH_{Coal,t} = CL_t \tag{A.86}$$

$$QH_{OIL,t} = OIL_t \tag{A.87}$$

A.3 Extensions to UK-ENVI for Chapter 4

Prices

$$PTNE_t = \frac{\sum_z PQ_{z,t}\cdot\bar{V}_z}{\sum_z PQ_z\cdot \bar{QH}_z} \tag{A.88}$$

$$PRE_t = \frac{\sum_E PQ_{E,t}\cdot\bar{V}_E}{\sum_E PQ_E\cdot \bar{QH}_E} \tag{A.89}$$

Consumption

$$C_{h,t} = YNG_{h,t} - SAV_{h,t} - HTAX_{h,t} - CTAX_{h,t} \tag{A.90}$$

Equation (A.90) *replaces equations* (A.28) *to* (A.32) *to produce myopic behaviour in household intertemporal consumption*

$$C_{h,t} = \left[\delta_h^E(\gamma RE_{t,h})^{\rho_e} + (1-\delta_h^E)TNEC_{h,t}^{\rho_e}\right]^{-\frac{1}{\rho_e}} \tag{A.91}$$

$$RE_{h,t} = \left(\gamma_h^{\rho e}\delta_h^E \cdot \frac{PC_{h,t}}{PRE_{h,t}}\right)^{\frac{1}{1-\rho e}} \cdot C_{h,t} \tag{A.92}$$

$$TNEC_{h,t} = \left(\gamma_h^{\rho ne}(1-\delta_h^E) \cdot \frac{PC_{h,t}}{PNEN_{h,t}}\right)^{\frac{1}{1-\rho_h{}^e}} \cdot C_{h,t} \tag{A.93}$$

$$QH_{ne,h,t} = \delta_h^{NE} \cdot \left(\frac{PC_{h,t}}{PQ_{ne,h,t}}\right)^{\frac{1}{1-\rho_h{}^{ne}}} \cdot QNTRA_{h,t} \tag{A.94}$$

$$QH_{e,h,t} = \delta_h^{NE} \cdot \left(\frac{PC_{h,t}}{PQ_{e,h,t}}\right)^{\frac{1}{1-\rho_h{}^e}} \cdot RE_{h,t} \tag{A.95}$$

Equations (A.33) *to* (A.39) *are indexed in 'h' to identify the differences between different household income groups.*

A.4 Extensions to UK-ENVI for Chapter 5

Prices

$$PF_t = \frac{\sum_f PQ_{f,t} \cdot \bar{QH}_f}{\sum_f PQ_f \cdot \bar{QH}_f} \tag{A.96}$$

Consumption

$$C_t = YNG_t - SAV_t - HTAX_t - CTAX_t \tag{A.97}$$

Equation (A.97) *replaces equations* (A.28) *to* (A.32) *to produce myopic behaviour in household intertemporal consumption*

$$C_t = \left[\delta^{TR}(TR_t)^{\rho_{m,a}} + (1-\delta^{TR})A_{h,t}^{\rho_{m,a}}\right]^{-\frac{1}{\rho_{m,a}}} \tag{A.98}$$

$$TR_t = \left(\gamma_h^{\sigma_{m,a}}\delta^{TR}\cdot\frac{PC_t}{PTR_t}\right)^{\frac{1}{1-\rho_{m,a}}}\cdot C_t \tag{A.99}$$

$$A_t = \left(\gamma^{\sigma_{m,a}}(1-\delta^{TR})\cdot\frac{PC_t}{PA_t}\right)^{\frac{1}{1-\rho_{m,a}}}\cdot C_t \tag{A.100}$$

$$TR_t = \left[\delta^{V}(\gamma VC_t)^{\rho_{v,f}} + (1-\delta^{V})F_t^{\rho_{v,f}}\right]^{-\frac{1}{\rho_{v,f}}} \tag{A.101}$$

$$VC_t = \left(\gamma_h^{\sigma_{v,r}}\delta^{V}\cdot\frac{PTR_t}{PV_t}\right)^{\frac{1}{1-\rho_{v,f}}}\cdot TR_t \tag{A.102}$$

$$F_t = \left(\gamma^{\sigma_{v,r}}\delta^{F}\cdot\frac{PTR_t}{PF_t}\right)^{\frac{1}{1-\rho_{v,f}}}\cdot TR_t \tag{A.103}$$

$$QH_{a,t} = delta^{A}\cdot\left(\frac{PC_t}{PQ_{a,t}}\right)^{\frac{1}{1-\sigma_a}}\cdot A_t \tag{A.104}$$

$$QH_{veichles,t} = VC_t \tag{A.105}$$

$$QH_{fuels,t} = F_t \tag{A.106}$$

Time path of investment

Equations (A.48) *to* (A.52) *are substitute by the following equations, in order to produce the time path of myopic investment.*

$$I_{i,t} = v \cdot \left[KS^*_{i,t} - KS_{i,t}\right] + \delta \cdot KS_{i,t} \tag{A.107}$$

$$KS^*_{j,t} = \left(A^{x\rho^X_j} \delta^k_i \cdot \frac{PY_{j,t}}{uck_t}\right)^{\frac{1}{1-\rho^x_j}} \cdot Y_{i,t} \tag{A.108}$$

A.5 Glossary

Set	
$i, j \ i = j$	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
$fins(\subset dins)$	the set of foreign institutions
$h(\subset dngins)$	the set of households
$Z(\subset i)$	the set of energy sectors including transport
$E(\subset i)$	the set of energy sectors excluding fuels transport
$NE(\subset i)$	the set of non-energy
$(a \subset i)$	the set of non-private transport
$(m \subset i)$	the set of private transport

$(v \subset m)$	the set of motor vehicles
$(r \subset m)$	the set of refined fuels
Prices	
$PY_{i,t}$	value added price
$PR_{i,t}$	regional price
$PQ_{i,t}$	output price
$PIR_{i,t}$	national commodity price(regional+RUK)
w_t	unified nominal wage
wb_t	after tax wage
$rk_{i,t}$	rate of return to capital
Pk_t	capital good price
UCK_t	user cost of capital
λ_t	shadow price of capital
Pc_t	aggregate consumption price
PE_t	consumption price of energy
PNE_t	consumption price of non-energy
PRE_t	consumption price of residential energy
$PNEN_t$	consumption price of non-energy and transport
PTR_t	consumption price of private transport
PA_t	consumption price non private transport
PV_t	consumption price motor vehicles
PR_t	consumption price refined fuels

PG_t	aggregate price of Government consumption goods
ex	exchange rage (fixed)

Endogenous variables

$X_{i,t}$	total output
$R_{i,t}$	regional supply
$M_{i,t}$	total import
$E_{i,t}$	total export (interregional+regional)
$Y_{i,t}$	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
$V_{i,t}$	total intermediate inputs in i
$VR_{i,j,t}$	regional intermediate inputs
$VM_{i,j,t}$	ROW intermediate inputs
$VIR_{i,j,t}$	national intermediate inputs (Scotland+RUK)
$VI_{i,j,t}$	RUK intermediate inputs
G_t	aggregate Government expenditure
$QG_{i,t}$	Government expenditure by sector i
$QGR_{i,t}$	regional Government expenditure by sector i
$QGM_{i,t}$	national Government expenditure by sector i

C_t	aggregate household consumption
Ec_t	household consumption of energy
NEc_t	household consumption of non-energy goods
CO_t	household consumption of coal and oil
EG_t	household consumption of electricity and gas
ELE_t	household consumption of electricity
GAS_t	household consumption of gas
CL_t	household consumption of coal
OIL_t	household consumption of oil
$RE_{h,t}$	household consumption of residential energy
$TNEC_{h,t}$	household consumption of non-energy and transport
TR_t	household consumption of private transport
A_t	household consumption of non-private transport
VC_t	household consumption of motor vehicles
F_t	household consumption of refined fuels
$QH_{i,t}$	household consumption by sector i
$QHR_{i,t}$	household regional consumption by sector i
$QHIR_{i,t}$	regional+RUK consumption by sector i
$QHM_{i,t}$	imported consumption by sector i
$QV_{i,t}$	total investment by sector of origin i
$QVR_{i,t}$	regional investment by sector of origin i
$QIR_{i,t}$	ROW investment demand by sector i

$QVI_{i,t}$	RUK investment demand by sector i
$I_{j,t}$	investment by sector of destination j
$J_{j,t}$	investment by destination j with adjustment cost
u_t	regional unemployment rate
u_t^N	national unemployment rate
$R_{i,t}^k$	marginal revenue of capital
S_t	domestic non-government savings
Trf_t	household net transfer
$Trsf_{dngins,dnginsp,t}$	transfer among *dngins*
$HTAX_t$	total household tax
TB_t	current account balance

Exogenous variables

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

Elasticities

σ	constant elasticity of marginal utility
ρ_i^X	elasticity of substitution between intermediate and value added
ρ_i^Y	elasticity of substitution between capital and labour
ρ_i^A	elasticity of substitution in Armington function
ρ_i^x	elasticity of export with respect to term trade

ρ_i^e	substitution in consumption between energy and non-energy
ρ_i^g	substitution in consumption between CO and EG
ρ_i^o	substitution in consumption between coal and oil
ρ_i^{el}	substitution in consumption between electricity and gas
$\rho_{v,f}$	substitution between vehicles and fuels
$\rho_{a,m}$	substitution between transport and rest of goods

Parameters

$\alpha_{i,j}^V$	input-output coefficients for i used in j
α_j^Y	share of value added in production
$\delta_j^{Y,V}$	share in CES output function in sector j
$\delta_j^{k,l}$	share in value added function in sector j
$\delta_{i,j}^{vir,vm,vr,vi}$	share in CES function for intermediate goods
$\delta_{i,j}^{qvvir,qvm,qvr,qvi}$	share in CES function for investment
$\delta_{i,j}^{E,co,cl}$	share in CES function for household consumption
$\delta_{i,j}^{hr,hm}$	share of regional and imported consumption in CES
$\delta_{i,j}^{gr,gm}$	share in CES function for Government consumption
$\gamma_{i,j}^{vv,vir}$	shift paramenter in CES for intermediate goods
γ_i^f	shift paramenter in CES for household consumption
γ_i^g	shift paramenter in CES for Government consumption
$btax_i$	rate of business tax
$KM_{i,j}$	physical capital matrix
mps	rate of saving *dngins*

τ	rate of income tax
ρ	pure rate of consumer time preference
bb	rate of distortion or incentive to invest
δ	depreciation rate

B Industries included in the AMOS ENVI model

Table B.1: The industrial disaggregation of the AMOS ENVI 21- sectors model and corresponding Standard Industrial Classification (SIC) code in the 2009 Scottish SAM

Sector's name	Original sector from the 104 Scot IO table (SIC)
Agriculture, forestry and logging	01-03
Sea fishing and fish farming	03.1-0.32
Mining and extraction	06-09
Food, drink and tobacco	10.1-12
Textiles and clothing	13-15
Mfr Chemicals etc	20.3-23other
Metal and non-metal goods	24.1-25
Transport and other machinery	27-30
Other manufacturing	16-18, 31-33
Water, sewerage and waste	36-39
Construction	41-43
Distribution	45-47, 55-56
Transport	49.1-53
Communications, finance and business	58-71, 73-82
R&D	72
Education	85
Public and other services	84, 86-97
Coal extraction	05
Oil (refining and distribution)	19-20B
Gas	35.2-35.3
Electricity	35.1

C Industries included in the UK-ENVI model

Table C.1: The industrial disaggregation of the UK-ENVI 30 sectors model from the original 2010 UK IO table

Sector's name	Original sector from 2010 IO table (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

D Calculating the rebound effects

In general terms the rebound effect can be defined as one minus the ratio between actual energy savings (AES) and potential energy savings (PES) from an increase in energy efficiency so that:

$$R = 1 - \left(\frac{AES}{PES}\right) \cdot 100 \tag{D.1}$$

It is normally expressed in percentage. Depending on how AES are measured we may distinguish between different types of rebound effects.[5] In Chapter 4, I focus on the general equilibrium household rebound from an improvement in household residential energy use. However I also report the full general equilibrium household rebound across all the energy types (residential+refined fuels for private transport), and the economy-wide rebound, which is across the whole economy (household+industries) from an efficiency improvement in residential energy use. Finally I calculate the general equilibrium household rebound effect for each of the household group described in the paper. In this Appendix I show how these are calculated and what are the relations among these different measures of rebound.

For simplicity let us start from the case where all household groups improve energy efficiency at the same time in the use of residential energy use, and calculate the household rebound in the household's use of residential energy. This calculation will be identical if any household energy

[5] For extended discussions about different levels of rebound effects see for example Dimitropoulos (2007), Gillingham et al. (2016), Greening et al. (2000), Jenkins et al. (2011), Sorrell (2007), Turner (2013). For the specific taxonomy used in this thesis, please refer to Chapter 3, Section 3.2.

efficiency improvement occurs in a one or more household energy uses j that are not total household energy consumption, for j=*(electricity, gas, coal, refined fuels)*. For this reason here I refer to a generic household rebound in the use of j, which I call R_j.

The household rebound in j can be derived as:

$$R_j = \left(1 + \frac{\dot{E}_j}{\gamma_j}\right) \cdot 100 \tag{D.2}$$

where $\dot{E}_j$[6] is the proportionate change in household consumption of j and $\gamma_j > 0$ is the proportionate change in efficiency of j. When $-\dot{E}_j = \gamma_j$ the reduction in the residential energy consumption equals the increment in efficiency and there is no rebound effect. However, if the proportionate change in consumption of j is lower than the increase in efficiency there is rebound effect.

The total household rebound effect from an efficiency increase in j, R_C is derived as:

$$R_C = \left(1 + \frac{\dot{E}_C}{\gamma_j \alpha_j}\right) \cdot 100 \tag{D.3}$$

where $\dot{E}_C = \sum^j E_j$ and represents the proportionate change in total household energy consumption in response to an efficiency improvement in household consumption of j, and α_j is the initial share of consumption of j in total household energy use (across all $j = 1, ..., N$).[7] The term $\dot{E}_C/\gamma_j\alpha_j$ can be written as:

[6]Note that because here I are measuring AES as the proportionate change in E_j and this is expected to be negative, I need to change the sign in equation D.2.

[7]When energy efficiency is improved in all household energy uses I have that $\sum_{j=1}^{N} \alpha_j = 1$ and the term α disappears.

$$\frac{\dot{E}_C}{\gamma_j \alpha_j} = \frac{\Delta E_C}{\gamma_j E_j} = \frac{\Delta E_j + \Delta E_{C,-j}}{\gamma_j E_j} = \frac{\dot{E}_j}{\gamma_j} + \frac{\Delta E_{C,-j}}{\gamma_j E_j} \tag{D.4}$$

where Δ represents absolute change and the subscript $-j$ indicates all households energy uses excluding the specific j for which efficiency has improved. Substituting (D.4) into (D.3) and using (D.2) we have that:

$$R_C = R_j + \left(\frac{\Delta E_{C,-j}}{\gamma_j E_j} \right) \cdot 100 \tag{D.5}$$

Equation (D.5) indicates that the total household rebound depends on the net change in the aggregate household energy consumption. When the efficiency improvement in j results in a positive (negative) absolute change in all the other energy types $-j$ then the households total rebound is bigger (smaller) than the specific sector household rebound.

Finally, I derive the full economy-wide rebound as:

$$R_T = \left(1 + \frac{\dot{E}_T}{\gamma_j \beta_j} \right) \cdot 100 \tag{D.6}$$

where $\dot{E}_T$ measures the proportionate change in energy use across all the sectors in production and consumption and β_j is the initial share of energy use j in the whole economy. Accordingly, I can express the term $\dot{E}_T / \gamma_j \beta_j$ as:

$$\frac{\dot{E}_T}{\gamma_j \beta_j} = \frac{\Delta E_T}{\gamma_j E_j} = \frac{\Delta E_j + \Delta E_{C,-j} + \Delta E_{T,-C}}{\gamma_j E_j} = \frac{\dot{E}_j}{\gamma_j} + \frac{\Delta E_{C,-j}}{\gamma_j E_j} + \frac{\Delta E_{T,-C}}{\gamma_j E_j} \tag{D.7}$$

Where the subscript $T, -C$ indicates all energy uses in the economy except for household energy consumption. Substituting (D.7) in (D.6) and using (D.2) and (D.3) I obtain:

$$R_T = R_C + \left(\frac{\Delta E_{T,-C}}{\gamma_j E_j}\right) \cdot 100 \tag{D.8}$$

Equation (D.8) indicates that the economy-wide rebound will be larger (smaller) than the household rebound effect if there is a net increase (decrease) in the energy used by the rest of economy.

Let us now consider the case where only one household group h improves energy efficiency in consumption of j. In this case I derive household group's rebound in the use of j, $R_{h,j}$, and total household rebound from an efficiency improvement in the single group use of j, R_j. We can derive group's h household rebound in the use of j similarly to (D.2) so that:

$$R_{h,j} = \left(1 + \frac{\dot{E}_{h,j}}{\gamma_{h,j}}\right) \cdot 100 \tag{D.9}$$

where h is a the set for household groups, that is $h = (HG1, \ldots, HG5)$. To derive, the total household rebound across all groups from an efficiency improvement in j in only one group I use the following expression:

$$R_j = \left(1 + \frac{\dot{E}_j}{\gamma_j \beta_{h,j}}\right) \cdot 100 \tag{D.10}$$

where $\beta_{h,j}$ is the share of one group consumption of j in total household energy consumption. Again, even in this case I can write:

$$\frac{\dot{E}_j}{\gamma_j \beta_{h,j}} = \frac{\Delta E_j}{\gamma_j E_{h,j}} = \frac{\Delta E_{h,j} + \Delta E_{j,-h}}{\gamma_j E_{h,j}} = \frac{\dot{E}_{h,j}}{\gamma_{h,j}} + \frac{\Delta E_{j,-h}}{\gamma_j E_{h,j}} \tag{D.11}$$

And so by substituting (D.11) in (D.10) and using (D.9) and I have that:

$$R_j = R_{h,j} + \left(\frac{\Delta E_{j,-h}}{\gamma_j E_j} \right) \cdot 100 \tag{D.12}$$

where the subscript $-h$ indicates all the household groups except for those who are receiving the efficiency improvement. When the efficiency in one group's use of j increases the other groups might use more or less j. If they use more, than the total household rebound in the use of j will be bigger than the group's rebound in j and vice versa.

E Disaggregation of 2010 UK SAM household sector

For the purposes of this work, I use a 2010 UK SAM in which the household sector is disaggregated by income quintiles. The disaggregation has been carried out by the team of the Centre for Energy Policy, University of Strathclyde, with which I am currently working. Because the methodological documentation is not publicly available yet, here I briefly summarise the main steps of the disaggregation procedure. The income quintiles are determined following the approach adopted by the UK Office for National Statistics (ONS) in its Family Spending publication,[8] 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 following weekly gross income:

- 1st quintile 0-237 per week;
- 2nd quintile 238-412 per week;
- 3rd quintile 413-650 per week;
- 4th quintile 651-1,014 per week;
- 5th quintile over 1,015 per week;

Given the above income groups, the UK SAM is disaggregated in three distinct steps, following the methodology developed to disaggregate the

[8]Family Spending reports deciles so for this study two deciles at a time have been merged to create a quintile.

2009 Scottish SAM by the Fraser of Allander Institute (Emonts-Holley, 2016). The first step is the disaggregation of household final demand.

The main dataset required for this step is the table of the derived household variables, published as part of the LCFS. In this dataset, the household spending is reported in 12 spending categories (varying from food to manufactured goods to provision of services). The other dataset required is the household final consumption expenditure (HHFCe) table, which is published by the ONS. In the 2015 edition of HHFCe the outputs of the 104 UK industrial sectors included in the UK Industry x Industry Input-Output table, are aggregated into 36 categories of household final consumption. For this reason it is necessary to march the 36 categories of HHFCe to the 12 types of spending, through the use of an appropriate mapping matrix.

Following that, and by using the data from specific derived variables from the LCFS dataset, the spending of each quintile (as reported in LCFS) is disaggregated for each of the 104 sectors and the share of each sector's household consumption that is allocated to each quintile is estimated. Finally, final consumption for each of the quintiles and each of the SAM sectors is obtained by multiplying the shares of each quintile's consumption by the household consumption as reported in the UK SAM.

The second step is to disaggregate the income and expenditures of each quintile. Contrary to the previous step, for most types of income and expenditure, there is no clear derived variables to be used for the purposes of disaggregation. For this reason, a number of different derived variables from LCFS need to be used. Once the appropriate variables are identified, the disaggregation process essentially involves using the values to create coefficients, which are in turn used to allocate the appropriate share of each type of income/expenditure to each of the quintiles. Please note that in order to enhance the robustness of the sample a 3-year average data is used both in step one and two (Emonts-Holley, 2016).

The last step involves balancing the SAM. The CGE model requires a balanced SAM to generate results, i.e. the sum of each row is the same as the sum of the corresponding column. Even though the 2010 UK SAM was balanced, disaggregating the households leads to imbalances to each of the household quintiles. Therefore, it is necessary to re-balance the SAM. To do so, any discrepancies between the rows and the columns of each quintile is allocated to the income from capital formation entry of each quintile.